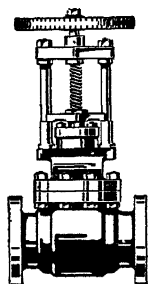


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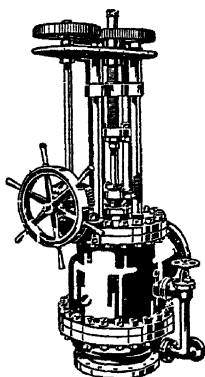
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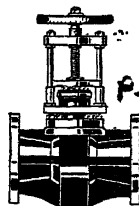
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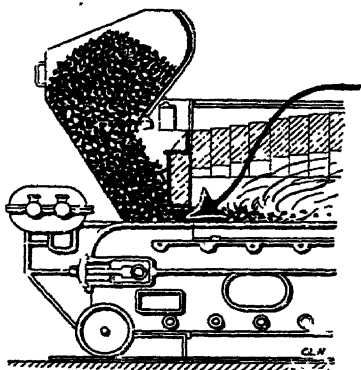
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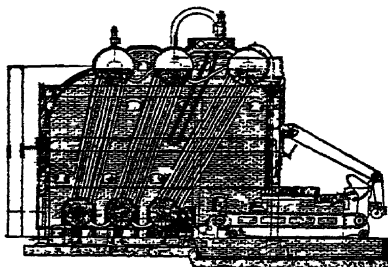
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POWER STATION EFFICIENCY CONTROL

-



TURBINE-ROOM, DALMARNOCK POWER STATION

Frontispiece

POWER STATION EFFICIENCY CONTROL

A TREATISE FOR THE POWER STATION ENGINEER
ON BOILER-ROOM EFFICIENCY, TURBINE-ROOM
EFFICIENCY, HEAT BALANCE CONTROL, METHODS
OF RECORDING AND TABULATING OPERATING
RESULTS AND KEEPING A DAY TO DAY CHECK
ON OPERATING EFFICIENCY

BY
JOHN BRUCE

A.M.I.E.E.

WITH AN APPENDIX BY

R. H. PARSONS

M.I.MECH.E., M.E.I.C., ASSOC.M.INST.C.E.

LONDON
SIR ISAAC PITMAN & SONS, LTD.
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PREFACE

THIS book is not a highly technical treatise, but should be looked upon rather in the nature of a talk to power station operating engineers, on the salient factors influencing efficient operation. The methods of efficiency control outlined in the following pages are those methods which are, or have been, used in the generating stations of the Glasgow Corporation Electricity Department, and the thanks of the author are due to R. B. Mitchell, Esq., M.I.E.E., Chief Engineer and Manager, for his permission to publish data referring to the operation of these stations.

The author desires to also record his thanks to the following gentlemen for their assistance: Mr. W. Ross, A.M.I.E.E., Mr. C. F. Wade, A.M.I.Mech.E., A.M.I.E.E., and Mr. F. Shakeshaft, A.M.I.E.E., also to the following firms: Messrs. Babcock & Wilcox, Ltd., The Underfeed Stoker Co., Ltd., The Lea Recorder Co., Ltd., Messrs. Glenfield & Kennedy, Ltd., The Cambridge Scientific Instrument Co., Ltd., Messrs. G. & J. Weir, Ltd., The Metropolitan Vickers Electrical Co., Ltd., Messrs. C. & A. Parsons, Ltd., The Mirrlees Watson Co., The British Thomson Houston Co., The American Babcock & Wilcox Co., who have supplied valuable data.

JOHN BRUCE, A.M.I.E.E.

GLASGOW,
1924.

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POWER STATION EFFICIENCY CONTROL

CHAPTER I

INTRODUCTORY

Good steam-electric power station design embodies amongst many three prominent factors: obtaining a kilowatt-hour with the minimum fuel consumption consistent with the cost of the fuel and return on investment; reliability; and operating convenience. When the point in efficiency is reached where the saving in fuel costs will no longer pay a fair return on the capital invested, and other charges necessary to obtain higher economy, the most economical condition has been reached and any further improvement in efficiency, only increases the cost of the kilowatt-hour delivered to the consumer.

Relation between Expenditure and Efficiency. Fortunately, the minimum cost of production coincides approximately with the point of maximum efficiency. Reliability is reflected in continuity of service and can be obtained by installing a minimum of equipment so well constructed that the possibility of failure is very remote. Improved design and construction have made this possible, and many of the practices considered in the past to be essential for increased reliability have been discarded. These two factors, reliability and efficiency, have been, and in fact still are, the greatest problems in power station design on which the attention of engineers has been centred for years. It is, however, comparatively recently that operating conveniences have received serious attention. It may require from two to three years to design and construct a plant, but its operation may continue for twenty or thirty years longer. Consequently, operating convenience should rank in importance with economy and continuity of service. In one sense, probably, it is of more importance, since if the plant is convenient to operate, the possibilities of its being kept in a high state of maintenance are greater, which will add to both the efficiency and reliability.

accuracy by means of a Pitôt tube ; coal consumption can be determined from grate speeds and thickness of fires ; and for a moderate expenditure a portable apparatus for the determination of CO_2 can be constructed. The steam consumption of turbines can be arrived at, providing the throat area of the nozzles, and the nozzle pressures and temperatures for the various loads be known, and from the data thus obtained the Willan's Line for each unit can be approximately plotted.

Though the accuracy is open to question, these methods at least furnish a basis for comparative plant performance.

The Willan's Line. The use of the Willan's line is to be recommended to all power station engineers. It is the simplest mathematical aid to a thorough understanding of the behaviour of steam plant. Its application is not limited to the steam consumption of the prime mover, as it can be applied to the solving of many questions relating to evaporation and coal consumption. As an aid to the analysing of the operating results of the station it is of very great value, and such a system is described and discussed in a later chapter. For the measurement of smaller quantities of steam, such as the supply to the steam-driven station auxiliaries, useful information can be obtained by the use of nozzle diaphragms and a few pressure gauges. The primary object of this book is to show the power station engineer-in-charge how the application of technical knowledge can help towards the obtaining and maintaining of efficient results.

In fact, technical knowledge is essential if the best results are to be obtained, and the foregoing remarks on what can be done in plants suffering from a lack of necessary instruments, will be dealt with at greater length in a later chapter. Space will not permit a discussion on the derivation of the various formulae given throughout the book, and interested readers are referred to the bibliography at the end.

Losses. In any coal-fired power station, the losses involved in the conversion of the heat energy of coal to electrical energy at the station bus bars, comprise the unavoidable losses inherent to the thermodynamic cycle, and other losses over which the station engineer can exercise some control. Therefore, to keep these losses at a minimum, the operating engineer must have means in the form of modern scientific instruments, for quickly ascertaining the heat transference in every unit of the plant. He must train himself to think in terms of heat

and be fully familiar with the fundamental laws of transference of heat from one medium to another, the flow of gases, and the equivalence of mechanical, heat, and electrical energy. He must be familiar with the figures and conditions which he finds show the least loss of British Thermal Units in each unit of plant in his charge, and his endeavour, necessitating at all times eternal vigilance, must be to obtain and maintain the efficiency figures for which the plant has been designed.

Classification of Losses. In a steam-driven plant the heat energy streams may be divided into three separate circuits. The first consists of the heat stream liberated by the combustion of coal, the second is that of the feed-water and steam, and the third is that of the circulating water. A statement showing the relations of the various heat quantities carried by these heat streams is termed a heat balance statement, the values being expressed in lb. calories or British Thermal Units. In steam electric practice the generator output may be considered as a fourth circuit and the electrical values expressed as the B.T.U. equivalent of the kilowatt-hours. Calculations of heat quantities with the large units of plant now in use involve the handling of unwieldy figures if results are expressed in B.T.U.'s, and in some cases two new units based on the B.T.U. are used. These are the therm and the myriawatt. The latter is equivalent to 34, 150 B.T.U.'s per hour, or in other words, is ten times the equivalent of the kilowatt-hour.

In Fig. 1 is shown diagrammatically an elementary form of heat stream diagram which can be considered as representative of modern power station practice. No definite values have been assigned to the various paths, as each will be considered in detail in other chapters. Starting with a definite quantity of heat units liberated by the combustion of the coal in the boiler furnaces, the major portion is absorbed by the water in the boiler, in the economizer or air preheater, and by the steam in the superheater. This point is represented by *AB*. The paths turning to the right represent unrecoverable quantities of heat lost from the first heat stream. The second portion of the diagram represents the heat quantities carried by the steam to the main turbines, house turbines, and steam-driven auxiliaries. The inter-connected branches on the left of the main stream represent heat recuperation, from steam bled from a stage of the main turbines, from the exhaust of house turbines and steam-driven auxiliaries, and from the heat contained in the flue gases. The third portion of the

diagram from *CD* represents the electrical energy available for distribution, the paths turning to the right being the

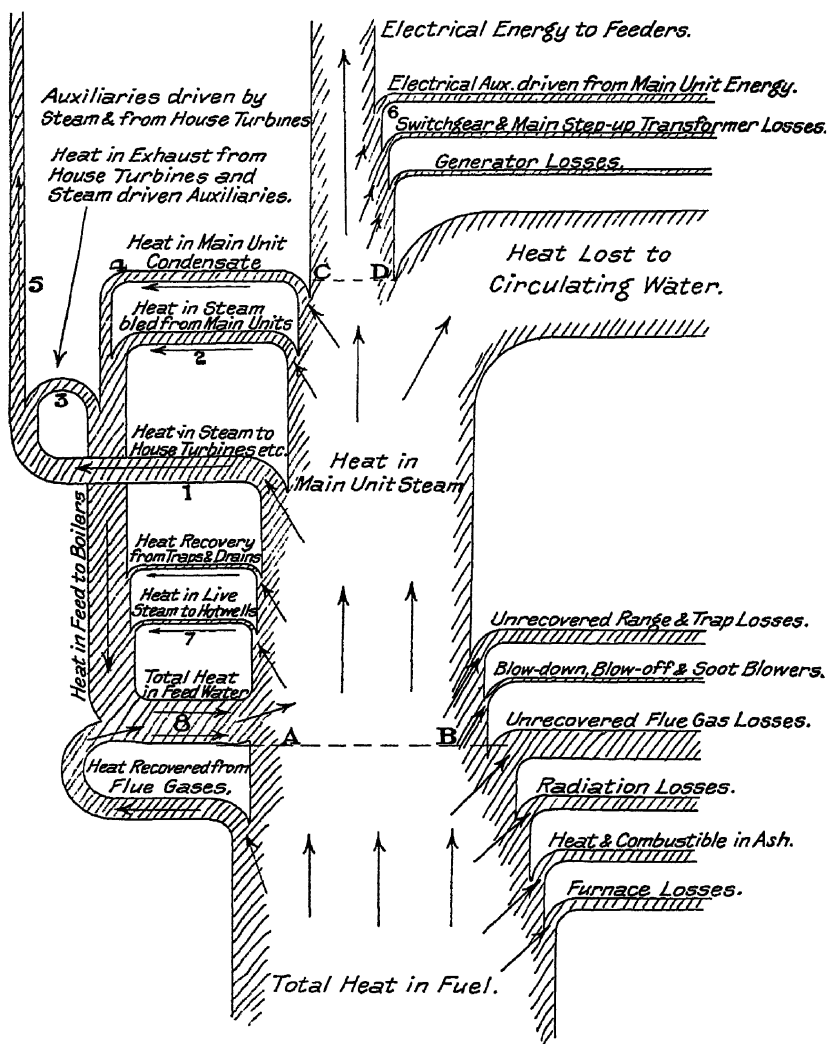


FIG. 1.—HEAT STREAM DIAGRAM OF MODERN POWER STATION.

electrical losses. The economical operation of the boiler and turbine-room plant as a whole depends upon the co-ordination of the several parts. For every value of the load carried by the station there is a combination of conditions which will give the maximum efficiency for that load, or the best efficiency

consistent with the reliability of service. By the intelligent control of the heat quantities or heat equivalents flowing in the paths 1, 2, 3, 4, 5, 6, 7, and 8, Fig. 1, the desired conditions can be arrived at. Operation of this portion of the power station plant with the fore-mentioned end in view, may be defined as heat balance control. No matter however carefully heat balance conditions have been worked out, and the best conditions found for boiler-room and turbine-room economical operation, the efficiency will not be maintained unless the operating staff take a keen interest in their duties.

•

CHAPTER II

BOILERS AND BOILER-ROOM EFFICIENCY

General. With the introduction and development of the steam turbine, which, with the exception of internal combustion machinery, is our most thermally efficient prime mover, and the rapid development of electrical machinery to suit the high speeds necessary for efficient turbine operation, the attention of engineers was directed to the boiler-room. The increasing cost of fuel and the necessity for conservating our coal deposits has also led to the striving for higher boiler and overall boiler-room efficiencies and, as has already been stated, it is in this part of the power station plant that the greatest economies and money-saving can be effected.

The importance of even a small gain in the overall efficiency should never be overlooked, and in the majority of the power stations throughout the country, an increase of the modest figure of 5 per cent at the least is possible. Even this small gain would represent a substantial decrease of the enormous amount of coal which is wasted annually.

For instance, consider a boiler plant having an average daily operating efficiency of 70 per cent, and consuming 400 tons of coal per day. If by some means this efficiency could be increased to 75 per cent a simple calculation shows that the coal consumed would be less by approximately 6·7 per cent, and with coal of average quality and present-day prices, say, 16s. per ton, this saving would represent in money £21 8s. per day. Allowing for week-ends, holidays, and the seasonal effect on load factor this daily saving would result in the substantial sum of approximately £6,000 per annum. Against this saving, of course, is the return on the capital outlay, maintenance, and other charges necessary for the means by which the saving has been obtained, but in many plants nothing more than the provision of modern boiler-room instruments with intelligent firemen under the control of an enthusiastic superintendent, is necessary to obtain and maintain gratifying results.

Table I shows the saving in fuel costs by increasing the overall thermal efficiency of a power station.

The modern boiler plant is now made up of several units of

BOILERS AND BOILER-ROOM EFFICIENCY

TABLE I

SAVING IN FUEL COSTS, BY INCREASING THE OVERALL THERMAL EFFICIENCY OF A POWER STATION; BASED ON COAL AT 16s. PER TON, AND HAVING A CALORIFIC VALUE PER POUND AS FIRED, SUCH THAT 120,000 BRITISH THERMAL UNITS COST ONE PENNY

British Thermal Units to Produce One Kilowatt-hour.	Station Overall Thermal Efficiency. Per Cent.	Coal Cost per Kilowatt-hour. Pence.
35,000	9.75	0.291
34,000	10.03	0.233
33,000	10.33	0.275
32,000	10.66	0.66
31,000	11.00	0.258
30,000	11.36	0.250
29,000	11.76	0.241
28,000	12.18	0.233
27,000	12.63	0.225
26,000	13.11	0.216
25,000	13.63	0.208
24,000	14.20	0.200
23,000	14.82	0.191
22,000	15.50	0.183
21,000	16.23	0.175
20,000	17.05	0.166
19,000	17.84	0.158
18,000	18.92	0.150
17,000	20.05	0.141

the water-tube type of boiler. The whole history of the evolution of this type of boiler, and a full treatment of the constructional details of boiler-room equipment is, however, outside the scope of this book. Present-day practice demands high pressures and superheats, rapid evaporation coupled with an insistency for higher efficiency and more economical working,

and steam generating units are now built capable of evaporating 100,000 lbs. of water per hour at steam pressures at and above 300 lbs. per sq. in. The tendency seems to be for still higher pressures. One large power station in this country is operating with a fair amount of success at 450 lbs. per sq. in., and the operating pressure of the 100,000 lbs. per hour boilers at the

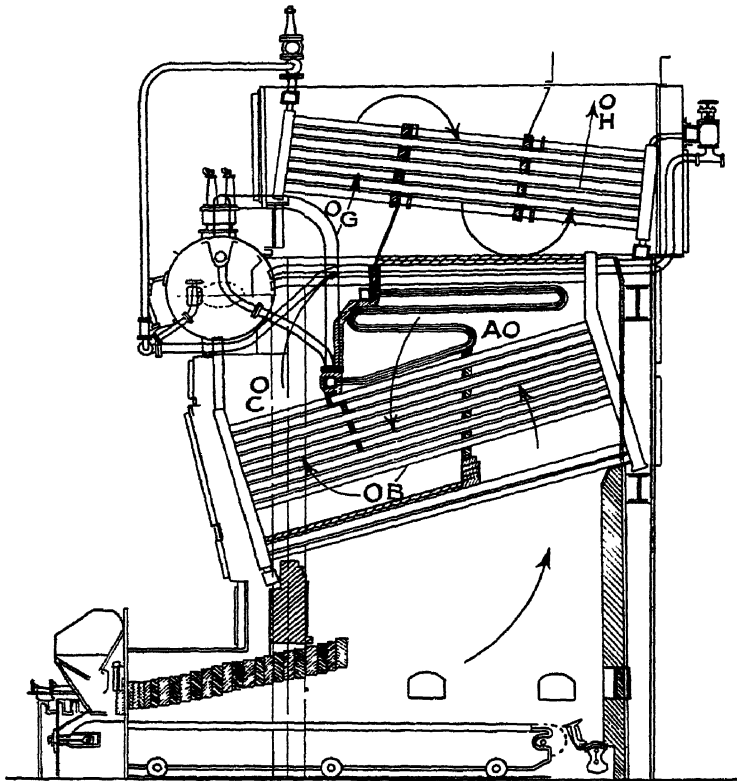


FIG. 2.—MODERN BOILER UNIT.

Gennevilliers Station, Paris, is 350 lbs. per sq. in. Owing to the properties of the material at present being used, the total temperature of the steam seems to have reached its upper limit at 750° F. A departure from recognized conventional practice, which is being watched with very great interest by power station engineers, is the construction of a new station for the Boston Edison Company on the Weymouth Fore River. The plant which will have an ultimate capacity of 300,000 kws. has many outstanding features.

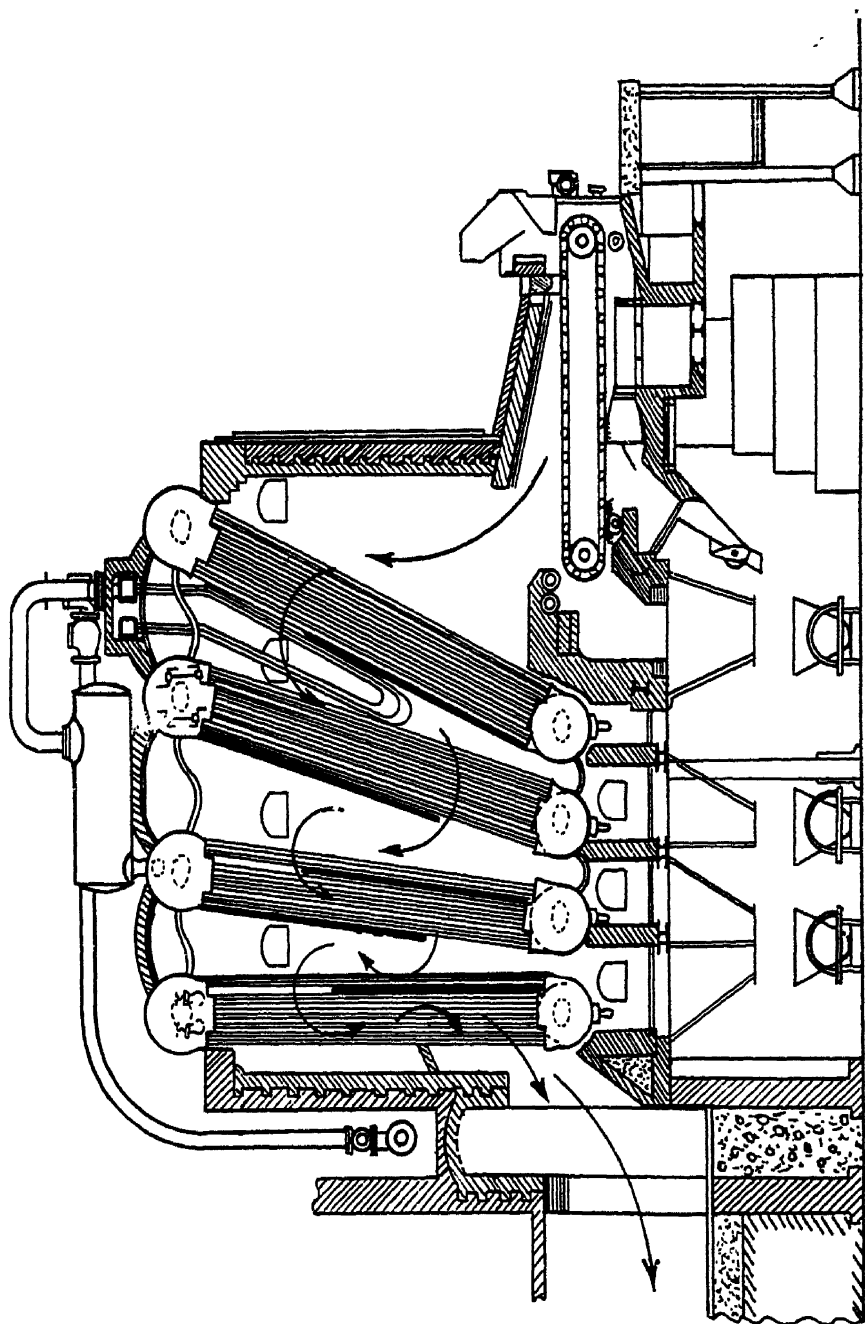


FIG. 3.—MODERN BOILER UNIT.

Steam, generated at 1,200 lbs. per sq. in. will first be utilized in three turbines each of 2,000 kws. capacity; exhausting from these at a pressure of 375 lbs. per sq. in. the steam is

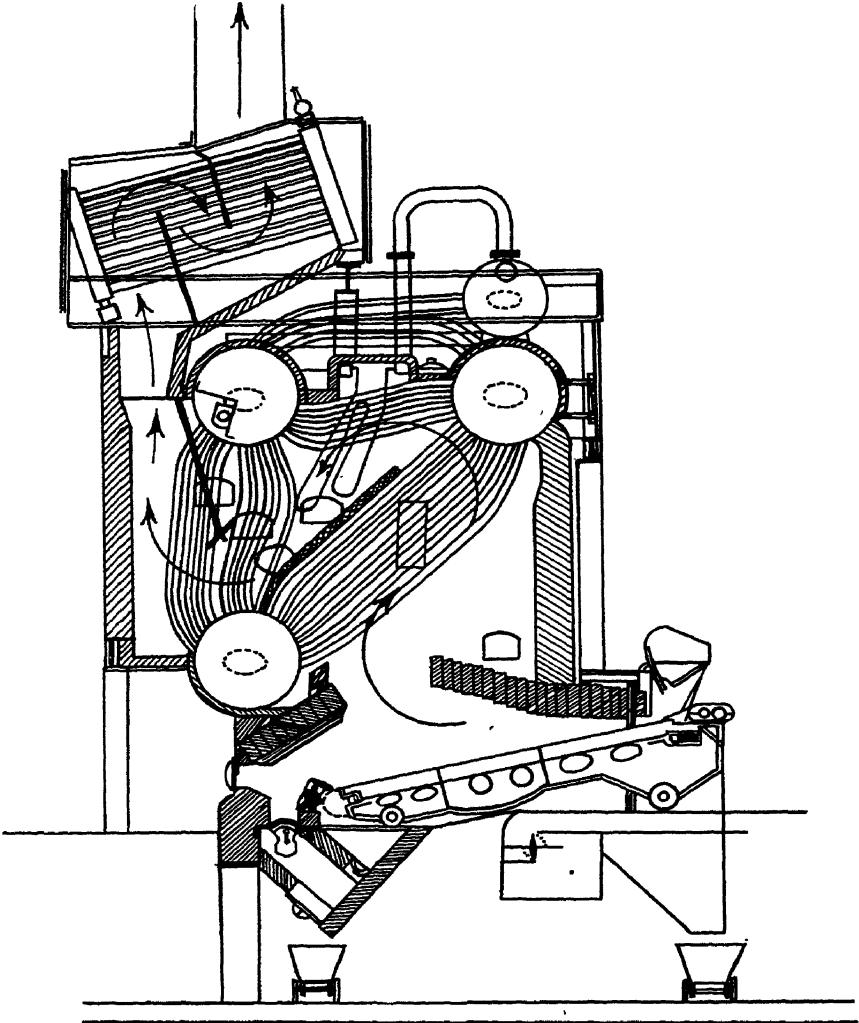


FIG. 4.—MODERN BOILER UNIT.

reheated to 700° F. and sent on to the main turbine which has a capacity of 30,000 kws.

With this combination of plant it is hoped that a kilowatt-hour will be produced to the outgoing feeders for an expenditure of 13,600 B.T.U.'s from the coal, representing a station overall

thermal efficiency of 25.00 per cent on full load, or in other words, with coal of a calorific value of 14,400 B.T.U.'s per pound, the consumption of the station will be in the neighbourhood of 0.94 lbs. per kilowatt-hour.

The noteworthy features of modern boiler units are the large combustion spaces, grate area, and heating surfaces, for rapid rates of heat liberation and absorption. Figs. 2, 3, and 4 show typical examples of modern boiler units representative of British and American practice. In some instances on large



FIG. 5.—NO. 1 BOILER ROOM, DALMARNOCK POWER STATION.

units the economizer is now built in, or superimposed on, the boiler setting, the whole being enclosed in a metal casing and not as in the past placed half-way along the flue, with some hundred square feet of leaky brickwork around it. This new position of installing the economizer involved difficulties in the way of corrosion owing to the use of steel tubes, but it is claimed that this difficulty can now be chemically overcome. To be able to operate the present plants at their highest efficiency at all times, is just as important as to improve the maximum efficiency over what it is at present.

Centralizing the control of operation of all boilers in one room is a development which is being watched with interest

by power station engineers, with the possibilities in view of doing in the boiler-room what has been done on the electrical side of the plant. With centralized control it would be possible, it is claimed, to operate the boilers at their highest efficiency for a given load, and the combination of equipment could be worked out that would give the most efficient heat balance for certain loads, and the plant operated on this schedule. Fig. 5 shows the interior of one boiler-room of a large modern power station. The instrument equipment for each boiler is mounted on panels fixed to the concrete supporting pillars on either side of the firing aisle.

Coal. Coal is the source of the motive power, for the generation of the bulk of electrical energy utilized in this country. A short description of the various classes of coal will therefore not be out of place. Nobody can state the age of the coal seams found in so many different parts of the world, or how long the supply will last, but the necessity of conserving our chief national treasure, one we are squandering by prodigally wasteful methods, ought to be emphasized, for scarcely one man in a thousand understands that the smoke pouring from countless chimney-stacks throughout the country represents the squandering of a great inheritance. The coal seams from which are drawn the supplies for industrial purposes in this country, may vary in age by many thousands of years, and from the characteristics the different deposits possess, may be classified as under—

- (a) Anthracite.
- (b) Semi-anthracite.
- (c) Bituminous coal.
- (d) Lignite, or brown coal.
- (e) Peat.

Each class is composed of carbon, hydrogen, oxygen, nitrogen, and sulphur, along with impurities consisting of silica, alumina, magnesia, lime, oxide of iron, and earthy matter. Generally speaking, the more carbon a coal contains, the greater will be its heating value. In the above group, anthracite is the oldest known form of coal, and is the richest in carbon content, containing as much as 90 to 95 per cent, while peat, which strictly speaking is not a true coal, consisting principally of moisture and more or less decomposed and carbonized vegetable matter, contains only 20 to 25 per cent of carbon. Anthracite, which is practically all fixed carbon,

has a deep black colour, a shiny, semi-metallic lustre, few joints and clefts, and is compact and sometimes iridescent. When burning it neither softens nor swells, kindles slowly and with difficulty, giving off a short yellow flame which changes to a faint transparent blue. Semi-anthracite is not so hard or dense and as it contains a greater percentage of gaseous matter, it kindles more readily and burns more rapidly than the true anthracite. Bituminous coals form the class of greatest importance to power station engineers. It is from this class that most coals in use are drawn. They consist of fixed carbon and what was at one time erroneously called bitumen, this latter is a mixture of hydro-carbons, which, when heated breaks down into gases, oils, and tars. This volatile content in bituminous coals varies over a wide range. The physical properties of this class are a vitreous, resinous or greasy lustre, a brittleness in structure, and a range in colour from dark brown to pitch black. Those nearest the semi-anthracite class have a high calorific value, burn without smoke, and are of the highest class for steam generating purposes. A distinguishing characteristic of the true bituminous coals is a yellow flame and smoke when burning. A further sub-division of this class may be made into caking and non-caking coals. Caking coals fuse and swell when heated, have a high hydro-carbon content, and are valuable in the manufacture of gas. Non-caking coals are preferable for steam-raising purposes, they do not fuse so readily and burn much more freely. Lignite and peat are coal in the earlier stages of formation and are not used for steam generation in ordinary power station practice, though in certain cases, where plants are situated near deposits of this class of fuel, experiments have been made with a briquetted type of this fuel.

Coke. Coke, which of course cannot be classed as a virgin coal, is the residue of fixed carbon and ash remaining after heating bituminous coals to a red heat without access of air. It is the porous material remaining after the volatile constituents have been driven off and has an average heating value of 14,000 to 14,500 B.T.U.'s per lb. In nature it may be compared to the anthracite family. It is occasionally used as a fuel for the generation of steam, but requires a special design of grate and forced draft to complete combustion with sufficient rapidity.

Classification of Coals. There are various methods for classifying the different coals, but owing to the manner in

TABLE II
CLASSIFICATION OF COALS

Cl. ss.	Elementary Composition. Per Cent.			Ratio O : H.	Fixed Carbon by Distillation. Per Cent.	Appearance of Coke.
	Carbon.	Hydrogen.	Oxygen.			
Lignite	66 to 74	5 to 6	23 to 20	5	40 to 50	
Long Flaming Dry Coal	75 to 80	5.5 to 4.5	19.5 to 15	4 to 3	50 to 60	Pulverulent
Long Flaming Fat or Coking Coals	80 to 85	5.8 to 5	14.2 to 10	3 to 2	60 to 68	Melted but friable
Caking Fat Coals	84 to 89	5 to 4.5	11.0 to 5.5	2 to 1	68 to 74	Melted, somewhat compact
Short Flaming Fat or Coking Coal	88 to 91	5.5 to 4.5	6.5 to 5.5	1	74 to 82	Melted, very compact
Lean or Anthracite Coals	90 to 93	4.5 to 4	5.5 to 3	1	82 to 90	Pulverulent
Anthracite	93 +	3 -	4 -	1 to 0.75	90 to 92	

(Underfeed Stoker Co., Ltd.)

which they grade from one to another, a precise classification is difficult. Many attempts in this direction have been made, and certain classifications are in use based upon the physical characteristics of the coal, and upon the content of volatile matter and calorific value. The following (Table II) is a classification founded upon the differences in composition as found from ultimate analysis. The ratios given are based on the fuel constituents alone, the impurities such as sulphur, moisture, and ash being disregarded. In discussing the value of a coal for steam-raising purposes, the terms efficiency, economy, and boiler capacity are liable to become confused. The fuels available for a power station will possibly be determined by the locality of the nearest coal field. Therefore a study of the coals available may show the advantage of using a low-priced coal that will give a furnace and boiler efficiency of 70 per cent, as against a higher priced coal giving an overall efficiency of 75 per cent. In fact, the criterion of performance of power station plant is not just the efficiency of the various units, but the effect of their performance on the coal bill. The size of the coal is also an important factor in obtaining the best results, and changing from one class to another may necessitate alterations in grate design. A grate which has to cope with varying qualities and sizes of coal must also be provided with sufficient fan-power to furnish a wide range of draft values. The following (Table III) is a classification of British coals with respect to size.

TABLE III

The following is a classification of British coal with respect to size—

<i>Name</i>	<i>Size</i>
Unclassified	As mined and without screening, thus containing from lumps as large as can be conveniently handled down to finest slack.
Rough	
Through and Through	
Run of Mine	
Hand Picked	From 18" cube down to 4" cube.
Large	

Sorted or Double Screened Coals—

Trebles	Nuts	$\left\{ \begin{array}{l} 3'' \text{ cube to } 2'' \text{ cube.} \\ 2'' \text{ cube to } 1\frac{1}{2}'' \text{ cube.} \\ 1\frac{1}{2}'' \text{ cube.} \\ 1\frac{1}{2}'' \text{ screen to } \frac{1}{2}'' \text{ screen.} \end{array} \right.$
Doubles		
Singles		
Pea		
Peas	Through $\frac{1}{2}''$ screen with fine slack removed.	
Pearls	Slightly smaller than Peas with fine slack removed.	

TABLE III—(contd.)

<i>Single Screened Coals—</i>	
<i>Name</i>	<i>Size</i>
Rough Slack	2½" screen with all fines.
2" Slack	Maximum size as designated by name, with all undersizes.
1½" "	
1¼" "	
1" "	
¾" "	
Fine Slack	Undersize from screening Peas.
Sweepings	Undersize produced by dealers in handling at wharfs and yards.
Culm	Fine Slack from Anthracite.
Dross	" " " Scotch Coals.
Gum	" " " Anthracites.
Duff	The name given in Scotland, and North of England and at some Welsh collieries, to the poorest qualities of coal, generally in a very fine state of subdivision produced by the dry system of grading and screening.
Smudge	The name employed for the above quality of coal from Midland and Yorkshire collieries.
Slurry	The smallest size produced in the washing of coal.

The present high cost of production is due to a great extent to the increased cost of coal, which besides deteriorating in quality, rose shortly after the period of the war to three or four times its pre-war price, and is even now double 1914 prices and in some cases considerably more. The economical generation of steam depends largely on the care exercised in the purchase of the fuel, and of late the question has been raised and discussed as to the establishment of some method by means of which a basis can be arrived at between consumer and supplier, regulating the price of the fuel. Isolated schemes have been suggested and in some cases put into operation, but we are some way off yet from arriving at a basis satisfactory to both parties. In the case of the larger power stations the supplies of coal will be drawn from many different collieries, and this coal is very likely made up of various qualities varying in calorific value from 9,000 B.T.U.'s to over 13,000 B.T.U.'s per lb. This means that it is difficult to burn it all economically, because the conditions suited to one class of coal may not suit another class.

Furnace Efficiency. Whatever class of coal is used the results obtained are greatly influenced by furnace design and the class of grate used, and it is now recognized that further improvement in overall efficiency is to a great extent dominated by this

factor. Furnace efficiency is determined by the amount of combustible in the ash discharged and the heat value of the gases ascending from the grate, the former being influenced by the type of grate used, and the latter by the air control, height, capacity, and general arrangement of the combustion space. Mechanical stokers, however, are now made which will burn anything from coke-breeze to highly bituminous coals with very slight alteration. The factors to be considered in the purchase of a coal are the price, heating value, ash content, and the ability of the contractor to furnish a supply uniform in quality and in quantity. The actual value of a coal as a steam producer cannot, of course, be judged entirely from its heating value, etc. Coals which have given the same figure for heating value, when tested in a calorimeter, may give widely different results when consumed beneath a boiler. Therefore, when placing orders for fresh supplies, previous performance under everyday operating conditions must also be taken into consideration.

Reserve Stock. Supplies must be arranged according to the rate of consumption, as coal kept in ordinary open storage spaces exposed to the full effects of the weather, rapidly deteriorates in calorific value. In a large power station the reserve stock of coal should be such that, with a fairly constant rate of delivery, the amount in stock will be sufficient for about two months' supply. Representative figures for large central stations in this country are—

Reserve coal stock—60 days' supply.

Boiler-room silos—24 hours' supply.

No coal when delivered at the station should ever, unless in cases of emergency, be put straight up to the boiler-room bunkers, but should be conveyed to the main storage, and all boiler-room supplies drawn from there. In this way the coal does not have to lie longer than necessary and suffer consequent weathering. Coal lying in storage for any length of time loses in heating value, due to the oxidation of the hydrogen and carbon, and this loss may be as high as 10 per cent in coal stored for a period of a year. The loss is greater in small coals than in large, due to the greater surface exposed. One method of overcoming the effect due to weathering is by storing the coal under water, by doing so all risks of spontaneous combustion are also eliminated. This method of storing is common practice in America in cases where coal has to be stored for

periods over one year. A log or card index system should be used to record coal deliveries, giving the name of the colliery, type of coal, weight, date delivered, and wagon number. This information should accompany the sample for analysis, and should be filed along with the chemical description of the coal. Since the heating value of the coal is the basis from which the boiler-room and overall station efficiency figures are calculated, it is necessary that all coal tests be conducted with the greatest accuracy.

Large undertakings invariably have a Power Station Tests Department where a chemist, or an engineer with a technical training in chemistry, can make these determinations. In many of the smaller stations, and often in those of considerable size, the calorific values of the coal consumed are rarely known, and no methods of recording and tabulating operating and technical data are used. In such cases it would be a sound investment for groups of these stations to employ a Tests' staff for the use of them all, so that methods for efficiency control could be instituted. Under the supervision of the right man, an all-round increase in efficiency would be bound to result.

Analysis and Determination of Heating Value of Coal. The usual determinations which should be made daily are a proximate analysis of a sample of the coal, as fired to the furnaces during the twenty-four hours of the preceding day, and a calorimeter test for heating value. A proximate analysis means the accurate determination of the moisture, volatile matter, carbon, sulphur, and ash in unit weight of the coal. An ultimate analysis which determines the content of moisture, carbon, hydrogen, oxygen, sulphur, nitrogen, and ash should be made on colliery samples and under certain conditions, on samples of coal consumed on boiler tests. The following is a list of the chemical apparatus necessary for making a proximate analysis of coal—

(a) One calorimeter, preferably of the bomb type with spare bomb, outfit to be complete with ignition battery, oxygen cylinders, and connections.

(b) Two large scale thermometers (N.P.L. certificate) for use with bomb, graduated to $\frac{1}{100}$ th° C.

(c) Chemists balance (sensitive to $\frac{1}{10}$ th of a milligram) with box of weights.

(d) Glass, graduated measuring vessels for water, the largest to have a capacity of 3 litres.

- (e) Pestle and mortar, coffee mill, and set of sieves 60 to 100 mesh.
- (f) Watch glasses, crucibles, and porcelain boats.
- (g) Bunsen burners and water-jacketed drying ovens with thermometers, or electrical furnaces and electrical water-jacketed drying ovens.
- (h) Two desiccators.
- (i) Large sink with supply of hot and cold water.

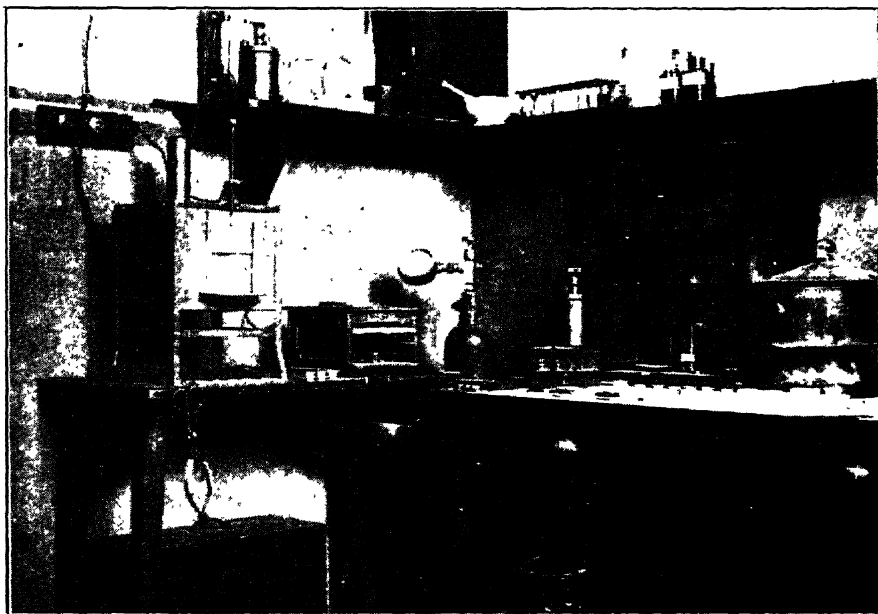


FIG. 6.—CHEMIST'S BALANCE, DRYING OVEN, ELECTRICAL FURNACE, DESICCATOR, ETC.

Many additions will no doubt suggest themselves, but the foregoing are the principal items necessary, and additions can easily be made enabling the determination of sulphur content, ultimate analysis, and water analysis to be carried out and, in fact, do all the chemical work in connection with the power station.

In the execution of any quantitative analysis, the operation of accurate weighing requires to be constantly carried out, and the engineer doing coal testing or any analytical work in connection with the power station should be able to use the balance rapidly and accurately. To facilitate weighing, the weights should be removed from their box and placed just within the balance case. For this purpose a stiff piece of

cardboard is prepared, marked off in squares to the same number as there are weights. The weights are placed in these spaces, and the value of the weight contained is written inside the square. Thus, when a substance is being weighed, the value can be quickly read off from the uncovered squares on the card. To adjust the balance the whole case is first of all trued up by means of the levelling screws. The horizontal position will be indicated by the spirit level on the floor of the balance case, or by the plumb line on the central pillar. To adjust the zero the scale pans and beam are gently set free from their supports. A gentle oscillation is then started if necessary, by a fanning movement of the hand over one of the scale pans. The index pointer will now swing over several divisions of the scale. If the pointer oscillates through an equal number of the divisions on each side of the zero of the scale, the balance is in adjustment. If the spaces traversed by the pointer are unequal an adjustment must be made by means of the small nuts at either end of the beam. When a substance is placed in one of the pans and weighed it ought to show the same weight in successive weighings. If the knife edges are faulty, different results will be obtained each time, also when each pan of the balance is loaded with weights of equal value, the equilibrium of the balance ought to be maintained when the weights are changed from one pan to another.

If such is not the case the arms of the balance are of unequal length. In weighing operations, place the substance to be weighed in the left-hand scale pan, and when counterpoising do not choose weights from the card at random but, starting with one judged to be slightly heavy, go through them in a systematic order until counterpoise is obtained. If the balance is fitted with a rider and beam, milligrams and fractions of a milligram are obtained by the adjustment of the rider. The balance case should be closed when making sensitive determinations of this nature. The weights should never be handled with the fingers, but by the forceps which are usually provided with the outfit, and in transferring weights or substances to be weighed the beam and pans should be lowered, neglect of this precaution will soon result in broken knife edges. A substance to be weighed must not be placed directly in the scale pan but, depending on its nature, should be weighed in a watch glass, or a container made of vitreosil, porcelain or platinum. Hygroscopic, efflorescent, and volatile substances and all substances whose weight is affected by exposure to the atmosphere must

be weighed in closed vessels. Finally, the balance and its case must be kept clean and should be permanently fixed in a position where it will be unaffected by vibration. Fig. 7 shows a group of the apparatus necessary for coal testing.

Sampling. The data obtained from the analysis of any coal will be valueless unless the greatest care is exercised in the collecting of the sample for analysis. This is especially so in the case of the daily sample of the coal consumed, as it may



FIG. 7.—BOMB TYPE CALORIMETER AND ACCESSORIES.

consist of so many different qualities of coal. As a sample, representative of the twenty-four hours' consumption is required, the quantity taken should not be less than 200 or 300 lbs. To prevent loss of moisture the container for the sample must be of airtight construction, and should be kept in the coolest part of the boiler-room. In cases where the moisture content and combustion rate of the coal varies greatly throughout the day, greater precautions must be taken, to ensure that the true moisture percentage is arrived at.

Every half-hour, oftener if the coal is varying greatly in quality, a sample is taken from the stoker-hoppers of the boilers on load. Three samples are necessary from each

hopper, one from either side, and one from the middle owing to the tendency for the larger pieces of coal to flow to the sides of the hopper as it leaves the chutes. At the end of each twenty-four hours the complete sample is thoroughly crushed, mixed, and quartered. One-quarter is put aside and the remainder again crushed, mixed, and quartered. This procedure is gone through until a sample of about 7 or 10 lbs. remains, all of which should pass a $\frac{7}{16}$ th in. mesh. The quartering and mixing must be carried out on a clean floor as quickly and thoroughly as possible to prevent loss of moisture. The sample for analysis is then put in an airtight tin and labelled. The quantity discarded during the quartering process is then weighed and returned to the stoker-hoppers, the weight being logged, and allowed for when calculating the daily operation results. In cases where the coal being fed to the furnaces has varied greatly in size, as well as in quality, the preparation for the sample for analysis requires very great care. One of the best methods to ensure that a representative sample has been obtained, is that described by David Wilson, O.B.E. (*Electrician*, 28th June, 1918). In this method a sample is selected from the large sample by quartering, until about 20 lbs. remains. Before preparing the sample for analysis the moisture is estimated. This is done by air drying the coal in a thin layer on a large tray, and noting the weight before and after drying. After the air drying is completed, the coal can be safely ground and mixed, without either losing or gaining an appreciable amount of moisture. This done, a smaller representative sample is made by separating the 20 lbs. sample by means of sieves into—

(a)	Over $\frac{1}{2}$ in. and under 2 ins. in size	.	.	lbs.	=	%
(b)	„ $\frac{1}{4}$ in. „ $\frac{1}{2}$ in.	„	.	„	=	%
(c)	„ $\frac{1}{8}$ in. „ $\frac{1}{4}$ in.	„	.	„	=	%
(d)	Under $\frac{1}{8}$ in. in size	.	.	„	=	%

These separate grades are now reduced in equal proportion and put in separate air-tight tins. The next step is a still further reduction of the sample for analysis. The contents of each tin are ground to pass a sieve having 30 meshes to the inch, thoroughly mixed, and 25 per cent taken from each. The four samples are then mixed and ground to pass through a sieve having 60 meshes to the inch. It is important that the whole of the sample passes through the sieve. After again thoroughly mixing, the coal is ready for analysis and calorimeter tests.

Sampling the deliveries of coal from the colliery must also be carried out carefully, though the chance of getting a representative sample is much greater than in the previous case, owing to the coal being more likely to consist of uniform quality. As each wagon is delivered to the coal handling centre, a sample is taken from eight points to a depth of a foot ; as the coal is discharged, eight more samples are taken, and so on until an average of about thirty samples have been obtained from the wagon. Each wagon is treated in a similar manner, and the sample pile dealt with as described for the sample drawn from the boiler room. It is often desirable to know the daily percentage of combustible carried over in the ash, and depending upon the system of ash handling plant installed, samples can be collected and dealt with in the same way as the daily coal sample.

Preparation of Sample for Analysis. The method of preparing for analysis will depend on the sampling method that has been adopted. If the sample has been prepared by the first described method, the quantity in the sample tin is next intimately mixed, and a sufficient amount taken for moisture, volatile matter, and ash determination. Another quantity, a pound or two should be taken to ensure getting as representative a sample as possible, is then ground with the mortar and pestle and finally in the coffee mill, which should be adjusted to grind as finely as possible, until the whole quantity passes through a 60-mesh sieve. This ground sample is reserved for the calorific value test. Each sample is put in a small air-tight tin, labelled, and is then ready for analysis. If the coal sample has been prepared by the second method described, no further preparation is necessary, and as the surface moisture has already been determined, the analysis can start with the estimation of the hygroscopic or inherent moisture.

The following definitions are used in connection with proximate analyses. *Fixed carbon* is the carbon remaining after the distillation of the volatile matter. It must not be confused with *total carbon* as found by ultimate analysis. *Combustible* may be defined as that portion of the dry coal, left after subtracting ash and total moisture. *Volatile matter* is the total combustible minus the fixed carbon, and includes gases, hydro-carbons, free oxygen, and nitrogen, the latter two are non-calorific. *Ash* is the residue left after the moisture has been driven off and the combustible absolutely consumed.

Determination of Free Moisture. The tin containing the unground sample is opened in the laboratory, and a representative sample weighing 10 grams is taken. This is most suitably done by weighing the sample out on to a previously weighed watch-glass. It is then put in one of the desiccators and dried, until on repeated weighings no further loss occurs.

A desiccator (see Fig. 6) is a glass jar with a glass cover, ground to a fit, an air-tight joint can be assured if the lip of the jar and cover are smeared with vaseline. A constricted portion half-way up the jar forms a shelf to support a perforated platform, on which the samples are placed when drying. The bottom of the desiccator contains the drying agent, which can be either pumice covered with sulphuric acid (commercial) or pure calcium chloride. The desiccator is also useful as a container for hygroscopic or dried substances, waiting to be weighed.

Determination of Inherent Moisture. After weighing the sample is transferred to the water-jacketed oven, which can be either heated electrically or by a Bunsen burner. It is dried in this oven at a constant temperature of 100°C ., until no further loss in weight occurs on repeated weighing. Care must be taken not to let the temperature of the oven rise, otherwise there is a danger of distilling off a portion of the lighter volatile matter, also when weighing, the sample must be cooled in the desiccator, before being placed on the balance. In both the foregoing determinations it is sufficient if two weighings give the same reading. The free moisture plus the inherent moisture equals the total moisture.

Determination of Volatile Matter. Powder the 10 grams and take 2 grams in a platinum, nickel, or vitreosil crucible, which has been previously weighed. Cover the crucible with its lid and heat in a powerful Bunsen flame in a midget furnace, or electrical muffle furnace. In order that comparable results may always be obtained in different estimations, the size of the Bunsen flame, or the temperature and the position of the crucible in the electrical furnace, must always be the same. The temperature, recommended by Prof. Bone, at which the volatile test should be carried out is 900°C . and as an electrical muffle furnace provides the best means for carrying out the determination at that temperature, an ammeter can be kept in the furnace circuit, with its scale marked off in temperature gradations, thus providing, in conjunction with a resistance,

a ready means of temperature adjustment. A suitable size and type of furnace is shown in Fig. 6. When the flame of the gases has ceased issuing from beneath the lid, continue the heating for one minute longer. The crucible is then removed and placed in the desiccator to cool, and as soon as possible weighed without the lid. The weight of the residue represents the weight of the coke plus the ash. The difference in weight from the original weight is volatile matter.

Determination of Fixed Carbon and Ash. Replace the crucible containing the residue of coke and ash in the muffle furnace, or strong Bunsen flame, and continue the ignition until all carbon has been burned off. The residue is ash, and the difference in weight between it and the previous weighing is fixed carbon.

Determination of Sulphur. Sulphur in any appreciable amount is objectionable, especially in stations where there is no feed-water heating between the condenser and the economizers, and where the temperature at the economizer inlet may be as low as 85° F. With low inlet water temperature to the economizer there is the possibility of condensation of the moisture in the flue gases, with the formation of sulphurous acids, which will rapidly attack the economizer pipes, especially at the inlet end of the economizer. The following is a good method for the sulphur determination. Weigh accurately 1.5 grams of the powdered coal into a suitable crucible, mix intimately with four times its weight of finely-powdered anhydrous Na_2CO_3 , by adding the Na_2CO_3 to the coal. The mixture must not be further stirred during the heating. Partially cover the crucible with its lid and apply heat gently, gradually raising the temperature to visible redness, then to a dull red heat, continuing the heating at this temperature for an hour. Cool the crucible and treat the mass with water, filtering the solution into a beaker. Add a few drops of bromine water to the filtrate, acidify with HCl , and boil the liquid till the bromine is removed. Precipitate the sulphate as BaSO_4 , and calculate the weight of sulphur. Factor for calculating S from $\text{BaSO}_4 = 0.13732$.

When starting a proximate analysis, a sheet tabulated with the necessary calculations to be made, should be prepared, so that only the various weights as they are determined need to be filled in. The following (Table IV) is an example of such a sheet. From this data the percentage composition, the calorific values, and other particulars are entered in a coal

analysis log-book. Table V, page 30 is an example of the entries and particulars as they should be recorded.

Determination of Heating Value. The heating value of a coal is determined by securing complete combustion of a representative weighed sample of the fuel, and measuring the rise in temperature of a weighed quantity of water, and the various parts of the apparatus. There are many types of calorimeter on the market. Those of the bomb type are considered, if used by an expert operator, to give the most accurate results. Calorimeters of this class essentially consist of a cylindrical bomb, four or five inches in diameter, with a gold or platinum lining. The sample of the fuel under investigation is placed in a receptacle within the bomb, which is then charged with oxygen to a pressure of several hundred pounds to the square inch. The whole is immersed in a known quantity of water and the sample fired electrically from a small battery. The temperature rise of the water is noted on a large scale thermometer to within 0.01°C , or by the use of a telescope and cathetometer, to within 0.002°C . The requirements of any calorimeter for coal testing are—

- (a) Combustion must be complete.
- (b) None of the heat generated must escape absorption by the water.
- (c) Radiation error must be small.
- (d) The thermometer error must be known.

The heating value, or calorific value, is calculated from the temperature rise of the water. As a certain amount of the heat generated will be absorbed by the bomb and constituent parts, an allowance has to be made for them. From their weight and specific heat, the water equivalent of the apparatus can be calculated, but this figure is usually supplied by the makers, along with the testing outfit. Another method of standardizing the bomb is by burning substances of known calorific value, such as standard samples of pure cane sugar, naphthalene, and benzoic acid. The calorific value of a coal may be defined as the number of heat units liberated by the complete combustion of 1 lb. of the fuel, and the value may be expressed in British Thermal Units, pound-calories, gram-calories or kilogram calories. In all calorimetric work the great thing to aim at is accuracy, and expert operators can in many cases get results to within 0.3 of 1 per cent.

In power station work the determinations of the calorific values of the coal should be left to the one man, for if it is

TABLE IV
 SAMPLE RECEIVED FROM CADZOW COLLIERIES
Date Delivered . . . 10th August, 1922
Class of Coal . . . Washed Singles

Analysis of Sample.	Percentage Composition.	
	Dry.	As Delivered.
<i>Free Moisture</i> (sample = 10 grams)—		
First weight of glass + sample . . .	22.400 grms.	
Final " " " + " . . .	21.553 "	
diff. . .	0.847 "	8.47
<i>Inherent Moisture</i> —		
First weight of glass + sample . . .	21.553 grms.	
Final " " " + " . . .	21.300 "	
diff. . .	0.253 "	2.53
<i>Volatile Matter</i> (sample = 2 grams, moisture free, coal)—		
First weight of crucible + sample . . .	13.405 grms.	
Final " " " + " . . .	12.769 "	
diff. . .	0.636 "	31.80 28.28
<i>Fixed Carbon</i> —		
First weight of crucible + sample . . .	12.769 grms.	
Final " " " + " . . .	11.574 "	
diff. . .	1.195 "	59.75 53.18
<i>Ash</i> —		
Final weight of crucible + sample . . .	11.574 grms.	
Original weight of crucible . . .	11.405 "	
diff. . .	0.169 "	8.45 7.54

carried out by one man one day and another man the next inaccurate figures will result. A well-known expert on combustion says: "A heat value determination is an extremely difficult thing to make with accuracy. An ordinary laboratory should not be trusted, as it requires high-priced calorimeters and involves skill and experience. There are a great many calorimeters, some of which are not dependable to within 500 B.T.U.'s. There is no such thing as a calorimeter that anybody can use and be sure of accurate results."

TABLE V

Date Tested.	Power Station or Colliery.	Class of Coal.	Date Delivered or Consumed.	Condition.	Calorific Values.	Total Moisture %.	Volatile Matter %.	Fixed Carbon %.	Ash %.	Sulphur %.	Remarks on Coke, Ash, etc.
23/11/22	Cadzow Colliery	Washed Singles	22/11/22	Dry	13,540		31.8	59.75	8.45		
				As Delivered	12,051	11.0	28.28	53.18	7.54		
24/11/22	Dalmarnock Power Station	Mixed Pearls and Singles	23/11/22	Dry	11,690		27.3	54.6	18.1		
				As Fired	10,406	11.0	24.3	48.6	16.1		
24/11/22	Port Dundas Power Station	Singles	23/11/22	Dry	12,610		26.88	58.27	14.85		
				As Fired	11,828	6.21	25.19	54.7	13.9		

The Bomb Type of Calorimeter. The component parts of one type of bomb calorimeter are shown in Figs. 6 and 7, and in Fig. 8 a sectional elevation of the parts assembled for a calorific value determination. The sample for investigation is taken from the air-tight tin containing the ground coal, three or four grams, sufficient for making a check test should

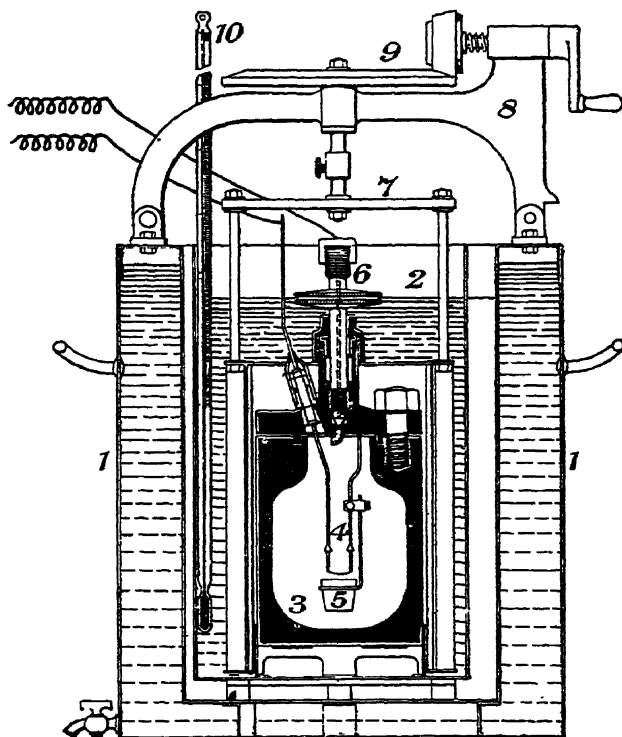


FIG. 8.—THE SARCO BOMB CALORIMETER.

- | | | |
|----------------------|--------------|-------------------|
| 1. Outer container. | 5. Crucible. | 8. Bracket. |
| 2. Inner container. | 6. Valve. | 9. Stirring gear. |
| 3. Bomb. | 7. Stirrer. | 10. Thermometer. |
| 4. Electrical leads. | | |

the first prove unsatisfactory, are put on a watch-glass or other receptacle, and heated in a water-jacketed oven, at a temperature of 100°C . until all free and inherent moisture has been driven off. When this point is reached the sample is rapidly transferred to the desiccator and allowed to cool. One gram is then weighed, as quickly as possible, into one of the small crucibles for the bomb, and is then fixed to the carrier, supported by one of the electrodes projecting from the

cover. A piece of fine copper wire is fixed across the electrodes to act as a fuse and ignite the coal when the battery circuit is completed. The whole is then carefully lowered inside the bomb, and the cover secured by the nuts. A spigot on the cover, and a lead joint on top of the body of the bomb, makes the assembled job gas-tight. The valve is then opened a few turns and connected to the oxygen cylinder. Oxygen is allowed to flow into the bomb until a pressure of about 350 to 400 lbs. per sq. in. is registered on the gauge. Care must be taken not to admit the oxygen too rapidly, otherwise the coal may be blown from the crucible, and when combustion takes place, will affect the walls of the bomb. For the same reason, the bomb when being handled, must always be kept in an upright position. When sufficient oxygen has been admitted the cylinder and bomb valves are closed. The outer water-jacket is then filled with water to within half-an-inch of the top, and a carefully weighed, or measured quantity, usually 2,000 or 2,500 grams, is filled into the bomb water-jacket. The temperature of the water in the inner jacket should be at, or slightly below, room temperature, and that in the outer jacket a degree higher. Some experimenters prefer the inner jacket-water to be slightly higher than room temperature, while others prefer it to be slightly below. While there is no data to show which method is the better, the latter is usually adopted. It is claimed that by this means the radiation correction will be a minimum or entirely eliminated. The water temperatures being satisfactorily adjusted the bomb is immersed, as shown in Fig. 8, and the stirring gear connected up. Before igniting the coal the stirring paddle is kept in motion and readings taken of the temperature; when this is constant the firing circuit is completed and the temperature carefully read and noted. Stirring is now continued and readings of the temperature are taken until the highest point has been reached and the temperature shows a tendency to fall. The difference between the temperature immediately before ignition and the highest reading obtained is taken as the temperature rise of the water, and the calorific value of the coal may then be calculated from the following formula—

$$C = (W_1 + W_2) \times t \times 1.8$$

where C = calorific value of the fuel in B.T.U.'s per lb.

W_1 = weight of water in grams in inner water-jacket

W_2 = water equivalent (in grams) of apparatus

t = temperature rise of water in °C.

In very accurate calorimetric work corrections are applied for the burning of the fuse wire, nitrogen, and sulphur contents of the coal, and the radiation error of the calorimeter. The nitrogen will burn to nitric acid, and the correction factor is obtained by titrating the washings of the bomb with standard alkali, 1 c.c. of which equals five calories or nine B.T.U.'s.

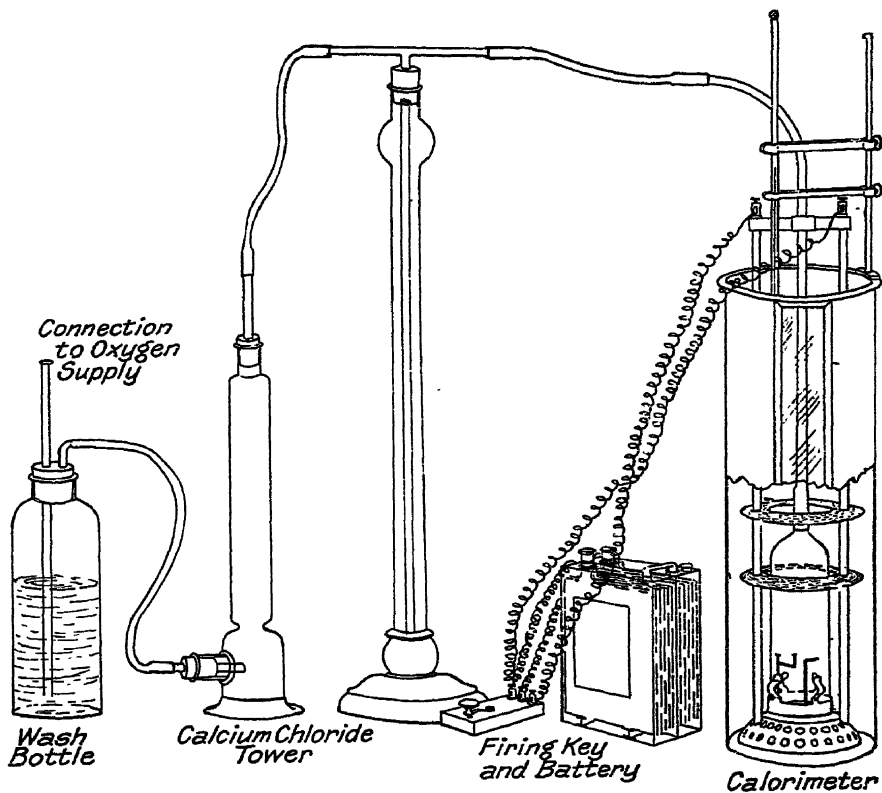


FIG. 9.—WILLIAM-THOMSON TYPE OF CALORIMETER.

The correction factor for the sulphur, which in the calorimeter burns to SO_3 , is calculated from the sulphur content as found in analysis. The radiation error is calculated from the rate of change of temperature before ignition, and the rate of change after the maximum temperature has been reached. After use, the interior of the bomb must be thoroughly washed out with hot water.

The "William-Thomson" Calorimeter. Another type of calorimeter extensively used is the "William-Thomson." It

is a simpler type of instrument than the bomb calorimeter, and while oxygen is used to effect combustion, it is admitted to the calorimeter in the form of a stream at atmospheric pressure. The apparatus consists essentially of two glass cylinders, the smaller of 2,000 c.c.s capacity and placed in the larger cylinder, which in some cases is made of metal. A lip around the edge of the inner cylinder serves to support it by resting on the top of the outer cylinder. The annular space between the cylinders forms an air jacket, preventing any appreciable change of temperature by the heat absorbed from the atmosphere. An inverted bell glass is placed beneath the water contained in the inner cylinder. The open end carries a perforated grating or ring, in which is fixed a brass cup, also perforated, which serves as a support for the crucible. The crucible, which is made of platinum, is supported, so that its upper level is above the level of the water in the bell-glass. Around the outside of the inverted bell are a series of wire gauze rings, which tend to circulate the water and compel uniform diffusion of the bubbles of gas through the water, as they leave the bottom of the inverted bell during combustion. Oxygen is led to the combustion space by means of a rubber tube, a cock being provided above the top of the ball-jar to regulate the flow. Ignition is effected by firing the fuel sample electrically. The weight of water, the water-equivalent of the apparatus, and the temperature of the water before and after combustion, give the necessary data from which the calorific value of the fuel being tested can be calculated (William-Thomson Calorimeter, Fig. 9).

The Ultimate Analysis of Coal. The ultimate analysis is used as a basis in one method of classifying coals. It can also be used to calculate the heating value of a coal, when a calorimetric determination cannot be carried out. It requires the use of much more chemical apparatus than is given in the list of necessary apparatus for proximate analysis, and should not be undertaken by the power station engineer, unless he is entirely familiar with all the details of the work, and is provided with a fully equipped chemical laboratory. The items considered in an ultimate analysis are moisture, carbon, hydrogen, sulphur, oxygen, nitrogen, and ash. When these constituents are used as a basis for classifying coals the results are computed to a dry coal basis, thus giving the relative proportions of hydrogen and oxygen in the coal, after the moisture has been eliminated.

The apparatus necessary for an ultimate analysis comprises a 25-burner furnace or electrical muffle, a combustion tube, one end of which is packed with copper oxide and chromate of lead, and the other end with a roll of oxidized copper gauze ; a porcelain boat for the sample of coal, a set of potassium hydrate absorption bulbs, a U-tube filled with calcium chloride, a supply of pure air and pure oxygen, and various other chemicals and chemical apparatus. Only an outline of the method of analysis can be given here, as a detailed description is outside the scope of this book.

In making the analysis a half-gram sample of the powdered, oven-dried coal is weighed in the porcelain boat, which is then placed in the combustion tube between the copper roll and the copper oxide. The combustion tube and contents are then thoroughly dried by preliminary heating, aided by a current of dry air. The furnace is lit, and the coal then burned by passing air, and finally oxygen, through the combustion tube. An absorption train has been previously connected up, consisting of the potassium hydrate bulbs and calcium chloride tubes. The carbon dioxide is absorbed by the potassium hydrate, and the water formed by the combustion of the hydrogen is absorbed by the calcium chloride.

The weights of the absorption apparatus before and after the test give the data from which the carbon and hydrogen are calculated. The nitrogen can be determined by absorbing any nitrogen oxide in a strong solution of potassium chromate, mixed with one-tenth its weight of potassium di-chromate, or it may be estimated by a process which converts the nitrogen in a certain weight of coal into sulphate of ammonia. From this, the amount of nitrogen can be calculated from the known composition of ammonia. The sulphur can be estimated as in proximate analysis. There is no simple method for directly estimating with accuracy, the proportion of oxygen present, but this is usually calculated by difference, after the percentages of all the other constituents have been found. The ultimate analysis can also be approximately determined by calculation from the proximate analysis of an air dried sample of the same fuel. The formulae for the calculations are based on numerous tests of a large selection of American coals, but as they are not applicable to all classes of coal, they are not included here. From the ultimate analysis the calorific value can be determined by substitution in Dulong's formula, which is based on the calorific values of the various constituents,

and the assumption that all the oxygen in the coal combines with one-eighth part of its weight of hydrogen—

B.T.U. per lb. of coal

$$= 14,544C + 62,028 \left(H - \frac{O}{8} \right) + 4,050S$$

where C , H , O , and S are the fractions of carbon, hydrogen, oxygen, and sulphur respectively in the combustible. The foregoing formula is given as a matter of interest, and as the calorific value calculated in this manner is open to certain sources of possible error, only the heating value as determined by a reliable form of calorimeter should be accepted as part of the analysis of a coal.

From the ultimate analysis referred to a dry coal basis, i.e. free from moisture and ash, the weight of air theoretically required to burn 1 lb. of the combustible can be calculated from the following formula—

Pounds of air theoretically required

$$= 11.52C + 34.56 \left(H - \frac{O}{8} \right) + 4.32S.$$

For example, it is required to find the theoretical quantity of air to burn a coal of the following composition: carbon 89 per cent, hydrogen 4 per cent, oxygen 5.5 per cent, sulphur 1 per cent, nitrogen 0.5 per cent. Let A equal the quantity of air per lb. of combustible, then substituting the percentage composition of the coal as fractions in the above equation—

$$\begin{aligned} A &= (11.52 \times 0.89) + \left\{ 34.56 \left(0.04 - \frac{0.055}{8} \right) \right\} + (4.32 \times 0.01) \\ &= 11.44 \text{ lbs. of air per lb. of combustible.} \end{aligned}$$

It must be clearly understood that the value of A , calculated in the preceding example is the amount of air expressed in lbs. for the complete combustion of one lb. of the *combustible*. The amount of air in practice required to burn one lb. of *coal* will have an entirely different value, depending upon the amount of ash and total moisture present in the fuel.

There are two recognized heating values for all fuels containing hydrogen. In the calorimeter the water formed by the combustion of the hydrogen is condensed, and gives up its heat to the water-jacket. When the same coal is consumed in the boiler furnace, the gases formed escape at temperatures well above the boiling-point of water, and the latent heat required for the vaporization of the water is therefore carried

off and is unavailable. These two heating values are defined as "the higher calorific value" and "the lower calorific value" respectively. The lower value approximates nearer than the higher calorific value to the heat, which unit weight of the fuel can develop in the conditions under which the fuel is actually burned in practice. There are various opinions as to the correct calorific value upon which power station efficiency calculations should be computed. The value used by the author is that value found after allowing for the percentage of moisture present in the coal, i.e. the gross calorific value of the coal as fired. Confusion is apt to arise if the basis, upon which efficiencies have been calculated, is not definitely stated. Either the gross calorific value of the dry coal as determined by the calorimeter or the same value corrected for moisture content, can be taken as the basis without materially affecting the results, but if the statistics are computed to a dry coal basis the weight of coal consumed must be corrected for moisture content.

The three principal factors governing the value of a coal for steam generating purposes may be taken as heating value, and ash and moisture contents. The effect of moisture in coal is to reduce the efficiency of the furnace in which it is consumed by increasing the heat carried away as latent heat in the water-vapour; it allows the escape of a larger quantity of free hydrogen, and retards the rate of combustion, due probably to the dilution of the oxygen by a large quantity of water-vapour. Theoretically, moisture in coal is generally detrimental, but in some bituminous coals the possible loss in efficiency is more than counterbalanced by the moisture content producing a mechanical action, which assists combustion instead of retarding it. In transit between colliery and power station, moisture in the coal is a "dead weight," and the consumer ought to continually bear in mind that it is heat units he is purchasing, and that any excess above the minimum moisture at the colliery is a pure loss.

The effect of ash content of a coal is to lower the efficiency of combustion as the ash content increases.

Coals high in ash require a greater draught, due to the ash forming an insulating layer so that the oxygen cannot come in contact with the coal. The increase in draught will also result in a greater leakage of air through the furnace walls and boiler setting. Coals in which the ash tends to clinker will result in clogging the fuel bed, and further retarding and

disturbing the correct distribution of air for combustion. From tests carried out on a chain grate stoker, with increasing percentages of ash artificially mixed with the coal, one authority on boiler-house problems came to the following conclusion. Up to 35 per cent of ash the efficiency dropped gradually, and above 40 per cent of ash it was impossible to generate steam. Like moisture, ash also is a "dead weight," and the presence of an undue proportion of ash in a coal increases the freight and handling charges of a given amount of combustible, and likewise the cost of removal and disposal of the refuse. A certain amount of heat is also lost in the removal of the accumulation of hot ash from the ash-pit and dumpers, and the higher the ash content of the coal the greater the amount of heat there will be carried away. More frequent removal of ashes will also be necessary, and unless the ash-pit discharge is sealed by water or some other means, the consequent inrush of cold air will considerably reduce the output of the boiler, besides imposing stresses on the water-tubes, due to the rapid temperature variations.

For efficient working, therefore, a coal with a high calorific value, low ash percentage, and low moisture content is most desirable, as its use also means less boilers in use for a given load, less dirt in flues and tube passages, with consequently longer steaming periods, and a saving in wear and tear of coal conveyor and ash removal plant.

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CHAPTER III

COMBUSTION OF COAL

The Chemistry of Combustion. The theory of combustion is very vaguely understood by many power station engineers, and a general knowledge of what is taking place during combustion of the coal in the boiler furnaces is of the greatest importance if efficient operating results are to be obtained.

To burn coal efficiently requires a high degree of technical skill, but provided the operating engineer has a knowledge of the fundamental principles, and his boiler plant is equipped with the necessary instruments, the control of the combustion process, to suit the load conditions and still maintain a maximum furnace efficiency, ought to be as simple as controlling the load on a generator.

There are also many engineers who regard the boiler-room as a place of much less importance than the turbine-room or switch gallery, and who only realize its existence when a shortage of steam and fall in pressure becomes noticeable.

To these engineers the boiler-room is to a great extent a secondary matter, and merely a place to burn enough coal to keep the plant running under the usual approximate conditions.

Combustion may be defined as any chemical action which takes place with the evolution of light and heat. In everyday language, substances are said to be combustible when they unite with the oxygen of the air with the production of light and heat. That is to say, during the combination of the substance with oxygen, so much heat is evolved that the remainder of the substance or its products become red hot, or even white hot, and give out light as well as heat. In some cases the substances must be heated before chemical action commences, but the total quantity of heat evolved is usually far in excess of that supplied to start the reaction. It is frequently stated that air is itself incombustible, but is a supporter of combustion. Neither of these statements are quite exact. Air supports the combustion of most, but not all substances which burn in oxygen. Some substances, like iron, burn in oxygen but not in air. Air itself can be shown to burn by the use of suitable apparatus.

There is a definite temperature at which every combustible substance combines rapidly with oxygen. Coal-gas, for instance, is kindled by a burning match, but not by one that is merely glowing.

Composition of Air. Atmospheric air consists almost entirely of two gases, oxygen and nitrogen, which are very much like one another in physical, though they differ widely in chemical, properties. Air also contains carbon dioxide in small quantities, and as air is always more or less damp, it contains larger or smaller amounts of water-vapour. At any definite temperature it can only hold a certain amount in a state of vapour which, below this temperature, is deposited in minute drops of liquid water, either as a fog or dew. This temperature is called the dew point.

Air also contains other gases such as argon, helium, neon, krypton, and xenon, but in very small quantities. The proportions of oxygen and of nitrogen and the other inert gases vary to a small extent, but far less than those of either water-vapour or carbon dioxide. The following table gives the approximate values for the proportion of the various constituents of the atmosphere. Moisture is not included—

Nitrogen	.	.	.	78.03 per cent by volume.
Oxygen	.	.	.	21.00 " "
Argon, etc.	.	.	.	0.94 " "
Carbon Dioxide	.	.	.	0.03 " "
Water-vapour	.	.	.	Variable.
Nitric Acid	}			Traces, but variable.
Ammonia				
Sulphur Dioxide				

In combustion calculations it is usual to consider only the oxygen and nitrogen. The generally accepted values of these gases are—

Oxygen	(O ₂)	per cent by volume = 21.00
Nitrogen	(N ₂)	„ „ volume = 79.00
Oxygen	(O ₂)	„ „ weight = 23.10
Nitrogen	(N ₂)	„ „ weight = 76.90

The following (Table VI), from *Steam*, gives the volume and weight of air at atmospheric pressure (29.92 ins. of mercury) at various temperatures.

Chemical Combination. When chemical actions are studied quantitatively, that is, from the point of view of the quantities of the substances taking part in them, they are found to obey

TABLE VI

PROPERTIES OF AIR

(From *Steam*, U.S.A. edition)

Temp. ° F.	Volume of 1 lb. in Cubic-ft.	Weight of 1 Cubic-ft. in lbs.	Temp. ° F.	Volume of 1 lb. in Cubic-ft.	Weight of 1 Cubic-ft. in lbs.	Temp. ° F.	Volume of 1 lb. in Cubic-ft.	Weight of 1 Cubic-ft. in lbs.
32	12.390	.080710	160	15.615	.064041	340	20.151	.049625
50	12.843	.077863	170	15.867	.063024	360	20.655	.048414
55	12.969	.077107	180	16.119	.062039	380	21.159	.047261
60	13.095	.076365	190	16.371	.061084	400	21.663	.046162
65	13.221	.075637	200	16.623	.060158	425	22.293	.044857
70	13.347	.074929	210	16.875	.059259	450	22.923	.043624
75	13.473	.074223	212	16.925	.059084	475	23.554	.042456
80	13.599	.073535	220	17.127	.058388	500	24.184	.041350
85	13.725	.072860	230	17.379	.057511	525	24.814	.040300
90	13.851	.072197	240	17.631	.056718	550	25.444	.039302
95	13.977	.071546	250	17.883	.055919	575	26.074	.038353
100	14.103	.070907	260	18.135	.055142	600	26.704	.037448
110	14.355	.069662	270	18.387	.054386	650	27.964	.035761
120	14.607	.068460	280	18.639	.053651	700	29.224	.034219
130	14.859	.067300	290	18.891	.052938	750	30.484	.032804
140	15.111	.066177	300	19.143	.052239	800	31.744	.031502
150	15.363	.065092	320	19.647	.050898	850	33.004	.030299

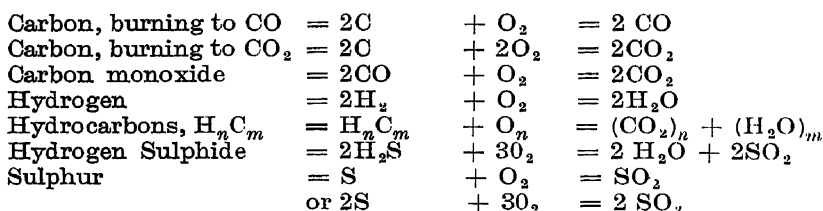
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certain laws, which have been established as the result of innumerable experiments. These laws are as follows—

- (a) Law of conservation of mass.
- (b) Law of constant or definite proportions.
- (c) Law of multiple proportions.
- (d) Law of equivalent or reciprocal proportions.
- (e) Gay-Lussac's law of gaseous volumes.

(a) **The Law of the Conservation of Mass.** *In every change, whether physical or chemical, the total mass of the substances before the change is equal to the total mass of the substances after the change: or, in other words, the total weight of the reacting substances is equal to the total weight of the products of the reaction.* It is this law which makes it possible to express chemical reactions in the form of equations.

For instance, in the combination of the exact amount of oxygen with the combustible elements in a coal all the principal reactions are expressed by the following equations—



All these are simple and easily understood.

(b) **The Law of Constant or Definite Proportions.** *The same compound always contains the same elements combined together in the same proportions by weight.* From this law it is obvious that if any of the constituents are present in excess of the proportion required for the formation of a definite compound, the excess will be left uncombined. For instance, in the formation of carbon dioxide (CO₂) the ratio of the weight of carbon to the weight of oxygen is *always* 1 to 2.66.

(c) **The Law of Multiple Proportions.** *When the same two elements combine to form more than one compound, the different weights of one of the elements which combine with a constant weight of the other bear a simple ratio to one another.* By a simple ratio is meant the ratio of two small whole numbers. For instance, carbon monoxide (CO) contains 42.85 per cent C, and 57.15 per cent O. Carbon dioxide contains 27.27 per cent C, and 72.73 per cent O.

From these percentages the ratio of the different weights of oxygen which combine with a constant weight of carbon, and the ratio of the different weights of carbon which combine with a constant weight of oxygen, can be calculated as follows—

42.85 parts of C combine with 57.15 parts of O

$$\therefore 1 \text{ part of C combines with } \frac{57.15 \times 1}{42.85} \text{ parts of O} \\ = 1.33.$$

27.27 parts of C combine with 72.73 parts of O

$$\therefore 1 \text{ part of C combines with } \frac{72.73 \times 1}{27.27} \text{ parts of O} \\ = 2.66.$$

Therefore the ratio of the different weights of oxygen which combine with a constant weight of carbon is *always* 1.33 to 2.66, i.e. 1 : 2. Continuing—

57.15 parts of O combine with 42.85 parts of C

$$\therefore 1 \text{ part of O combines with } \frac{42.85 \times 1}{57.15} \text{ parts of C} \\ = .75.$$

72.73 parts of O combine with 27.27 parts of C

$$\therefore 1 \text{ part of O combines with } \frac{27.27 \times 1}{72.73} \text{ parts of C} \\ = .375.$$

Therefore the ratio of the different weights of carbon which combine with a constant weight of oxygen is *always* .75 : .375 : i.e. 2 : 1.

(d) **The Law of Equivalent or Reciprocal Proportions.** *The proportions by weight in which two elements combine separately with a given weight of a third element are also the proportions by weight, or simple multiples of the proportions by weight, in which they combine with one another.*

Stated algebraically, the law is that if a parts by weight of the element A combine with c parts by weight of the element C , and if b parts by weight of the element B combine with the same weight c of the element C , then if the elements A and B form a compound, the weights of A and B contained in this compound will be in the proportion—

$$\begin{aligned} \text{weight of } A &= x a \\ \text{weight of } B &= y b \end{aligned}$$

when x and y are small whole numbers.

(e) **Gay-Lussac's Law of Gaseous Volumes.** *When chemical action takes place between gases, whether elements or compounds, the volumes of the reacting gases bear a simple ratio to one another and to the volume of the compound formed, if gaseous. The volumes, of course, in order to be comparable, must all be measured under the same conditions of temperature and pressure.*

For instance—

- 1 volume of carbon + 1 volume of oxygen give 2 volumes of carbon monoxide.
- 2 volumes of carbon monoxide + 1 volume of oxygen give 2 volumes of carbon dioxide.
- 2 volumes of hydrogen + 1 volume of oxygen give 2 volumes of water-vapour.

In all cases the ratios of the volumes are simple ratios. If one of the reacting substances is present in excess of the required proportions by volume, the excess is left uncombined.

From the foregoing laws it is thus seen that for a definite weight of a combustible element in the coal, a definite weight of oxygen is necessary for its complete combustion.

Space does not permit a fuller discussion on the fundamental laws which govern all chemical action, but a study of the chemistry affecting the boiler-room will well repay any engineer; in fact, it is necessary if the best results are desired from the operation of the boiler furnaces.

Not only will he be able to understand what is taking place during the process of combustion, but he will also be able to solve many problems concerning boiler water and scale.

No one can state with accuracy the reactions which take place in the fire-bed of a furnace. All that we can do at present is to measure the temperatures produced by the reactions and to measure the products of combustion. From the data thus available investigators have deduced various theories.

Combustion of Bituminous Coal. Generally speaking, when heat is applied to bituminous coal, the first result is its absorption by the coal and the liberation of gases from which flame is exclusively derivable. The constituents of these gases are entirely hydrogen and carbon in various proportions, and from the fact that they are composed of these two elements, these gases are generally termed hydrocarbons. Distillation of the lighter volatiles starts at temperatures below 300° F. At about 475° F. the distillation process is well under way, the rate of liberation gradually increasing up to 1,000° F. The maximum

TABLE VII
PROPERTIES OF GASES FROM (GAS & FUEL ANALYSIS FOR ENGINEERS)

GASES.	Chemical Formula.	Volume of Oxygen.	Volume of Air.	Volume of H ₂ O Vap.	Volume of CO ₂	Ignition ° F. Point.	B.T.U. per Cubic-ft.	
							60° Initial. 328° Final.	32° Initial. 32° Final.
Hydrogen	H ₂	0.5	2.39	1	0	1,085	263	345
Carbon Monoxide	CO	0.5	2.39	0	1	1,200	307	341
Methane	CH ₄	2.0	9.56	2	1	1,230	853	1,065
Ethane	C ₂ H ₆	3.5	16.73	3	2	1,140	—	1,861
Propane	C ₃ H ₈	5.0	23.90	4	3	1,015	—	2,657
Butane	C ₄ H ₁₀	6.5	31.07	5	4	—	—	3,441
Pentane	C ₅ H ₁₂	8.0	38.24	6	5	—	—	4,255
Hexane	C ₆ H ₁₄	9.5	45.41	7	6	1,400	—	5,017
Ethylene	C ₂ H ₄	3.0	14.34	2	2	1,010	—	1,074
Propene	C ₃ H ₆	4.5	21.51	3	3	940	—	2,509
Benzene	C ₆ H ₆	7.5	35.85	3	6	—	—	4,012
Acetylene	C ₂ H ₂	2.5	11.95	1	2	788	—	1,477

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temperature of an individual coal particle being reached after its volatile matter has been distilled off. Table VII on page 45 shows the principal hydrocarbon gases and the volume of oxygen and air necessary to burn 1 cu. ft. of these gases, together with the volume of the products of combustion.

Modern chain-grate stokers are usually provided with a firebrick arch over the first part of the firebed, and extending about two-thirds the length of the grate. This arch, when raised to a state of incandescence, rapidly ignites the hydrocarbon gases as they are distilled. It also serves to ignite the remaining coke or "fixed carbon" which requires a considerably longer time and higher temperature to effect complete combustion, than does the volatile hydrocarbons.

Perfect combustion is obtained when the combustible elements combine with their correct proportion of oxygen. Carbon is completely burned when it burns to CO_2 , that is, when it has united with its greatest possible amount of oxygen; but if one part of carbon unites or combines with only half the quantity of oxygen necessary to produce CO_2 , oxidation is incomplete, combustion is imperfect, and unless the CO thus produced is further oxidized in the combustion space, a loss of fuel takes place. One pound of carbon burning to CO_2 liberates from 14,000 to 14,500 B.T.U.'s whereas, when CO is the product of combustion of 1 lb. of carbon, only 4,000 to 4,500 B.T.U.'s are liberated. From the law of constant or definite proportions, the ratio of carbon to oxygen is 1 : 2.66, so that for the complete combustion of 1 lb. of carbon, 2.66 lbs. of oxygen are necessary; the reaction producing 3.66 lbs. of CO_2 , and liberating 14,500 B.T.U.'s. The equation representing the reaction may be written : $2\text{C} + 2\text{O}_2 = 2\text{CO}_2$.

From the ratio of carbon to oxygen it is a simple matter to now calculate the theoretical amount of air necessary for the combustion of carbon to CO_2 . From the parts by weight of oxygen and nitrogen in atmospheric air it is seen that one pound of oxygen is contained in 4.32 lbs. of air, therefore as 2.66 lbs. of oxygen are necessary for the complete combustion of carbon, the corresponding amount of air will be—

$$2.66 \times 4.32 = 11.5 \text{ lbs. of air.}$$

Since the oxygen is supplied to the furnace in the form of atmospheric air, the complete combustion of the above amount of carbon will result in the production of 12.52 lbs. of gas, the excess over 3.66 lbs. of CO_2 being nitrogen. From the law of

multiple proportions, it is seen that it is possible for carbon to unite with two distinct amounts of oxygen, producing in the one case CO, and in the other CO₂. These two gases have widely different properties, and if there is an insufficiency of the supply of oxygen to support the combustion, the tendency will be for the former gas to be formed. In such a case the ratio of carbon to oxygen will be 1 : 1.33, that is, 1 lb. of carbon will take up or combine with only 1.33 lbs. of oxygen, the product being 2.33 lbs. of CO, liberating only 4,000 to 4,500 B.T.U.'s. The equation representing the reaction may be written : $2C + O_2 = 2CO$.

In a well operated modern boiler unit the large combustion space facilitates the complete oxidation of the CO liberated from the firebed. It is for this purpose that many furnaces are provided with a means for supplying secondary air. The reaction may be expressed by the equation : $2CO + O_2 = 2CO_2$. This reaction liberates a further 10,000 B.T.U.'s per lb. of carbon involved, i.e. 14,500 minus 4,500. The B.T.U.'s liberated per lb. of CO taking part in the reaction is 4,300. In the reduction of CO₂ to CO, which may result due to deficiency or improper distribution of the air supply, the CO₂ takes up an additional molecule of carbon to form two molecules of CO. This reaction absorbs 5,500 B.T.U.'s per lb. of carbon in the CO₂, or 2,750 B.T.U.'s per lb. of carbon in the CO produced.

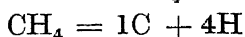
Hydrogen combines with eight times its weight of oxygen, therefore the oxygen in the coal will unite with one-eighth of its weight of the hydrogen in the coal or, in other words, the hydrogen equivalent in weight to one-eighth of the oxygen will not require oxygen for combustion from the atmosphere. As stated earlier, there are two heating values for fuels containing hydrogen, depending upon their initial and final temperatures during combustion ; 1 lb. of hydrogen combines with approximately 8 lbs. of oxygen to form 9 lbs. of water. The reaction may be expressed as : $2H_2 + O_2 = 2(H_2O)$. The amount of atmospheric air therefore necessary for the combustion of one pound of hydrogen will be—

$$8 \times 4.32 = 34.56 \text{ pounds.}$$

If the original temperature of the hydrogen and oxygen be taken as 64° F., and the products of combustion be cooled to this temperature, then 61,200 B.T.U.'s are liberated. It is impossible to attain this in practice as the final temperature of the

flue gases is well above 212° F., and the B.T.U.'s liberated from the combustion of 1 lb. of the hydrogen approximately 52,000 B.T.U.'s.

As has been stated the hydrocarbon gases are composed of hydrogen and carbon in various proportions, but from the atomic weights of their elements the oxygen and air necessary for their combustion and the products of such combustion can be easily calculated. Consider methane, the chemical formula of which is CH_4 .



and substituting atomic weights

$$\begin{aligned} 16 &= 12 + 4 \\ \text{or } 1 &= 0.75 + 0.25. \end{aligned}$$

Therefore 1 lb. of CH_4 contains 0.75 lbs. of carbon and 0.25 lbs. of hydrogen.

For the combustion of the carbon—

$$\begin{aligned} 0.75 \times 2.66 \\ = 2.00 \text{ lbs. of oxygen are necessary} \end{aligned}$$

and for the combustion of the hydrogen—

$$\begin{aligned} 0.25 \times 8 \\ = 2.00 \text{ lbs. of oxygen are necessary.} \end{aligned}$$

From the total oxygen required the amount of air can then be calculated—

$$\begin{aligned} &= 4.00 \times 4.32 \\ &= 17.28 \text{ lbs. of air.} \end{aligned}$$

Therefore from these figures the products of combustion of one pound of CH_4 will be—

$$\begin{aligned} &2.75 \text{ lbs of } \text{CO}_2 \\ &2.25 \text{ lbs. of } \text{H}_2\text{O} \\ &13.28 \text{ lbs. of } \text{N}_2 \end{aligned}$$

The combustion of 1 lb. of sulphur liberates 4,050 B.T.U.'s. Sulphur may occur in coal in three forms. It is commonly found as pyrite and in this form varies considerably in amount. Due to the weathering action on coal the sulphur present as pyrites may absorb oxygen from the atmosphere and have no heating value. It may also occur as a sulphate of iron, calcium or aluminium, and also in combination with coal substances of organic composition. During combustion one pound of sulphur unites with one pound of oxygen, and

forms one pound of sulphur dioxide, the reaction is as follows: $S + O_2 = SO_2$. If the temperature be lowered to the dew-point of the flue gases, as is often the case at the cold end of an economizer, a further reaction takes place. The SO_2 , combining with the condensed H_2O vapour from the oxygen content and the evaporation of the moisture, forms the dilute aqueous solution known as sulphurous acid (H_2SO_3). This acid being a reducing agent will take up a further molecule of oxygen and form the highly corrosive H_2SO_4 .

The foregoing discussion on the combustion of the various elements in the coal has been dealt with entirely on a basis of weight. From Gay-Lussac's law of gaseous volumes—

2 volumes of hydrogen (H) + 1 volume of oxygen (O) give
2 volumes of water-vapour.

2 volumes of carbon monoxide (CO) + 1 volume of oxygen give
2 volumes of carbon dioxide (CO_2).

It is not strictly true to speak of carbon as a gas, but it is easier to understand what is taking place during combustion if it is assumed to be so. From Gay-Lussac's law, it is thus seen that if the products of combustion in the flue gases be cooled to the temperature at which they entered the furnace, their volume will be equal to the volume of air supplied to the furnace. For instance, 1 lb. of carbon required 2.66 lbs. of oxygen, or 32 cu. ft. at $60^\circ F.$, to produce 3.66 lbs. of CO_2 . If the products of combustion be cooled to the original temperature, they will still occupy 32 cu. ft., but the weight will be 3.66 lbs. Nitrogen being an inert gas undergoes no change and will occupy its original volume.

The formula for the theoretical weight of air necessary for the combustion of 1 lb. of coal has already been given, and also a table showing the volume and weight of air at various temperatures. The weight and volume of air can also be computed from the formula: $VP = 53.4T$.

where V = volume of 1 lb. of air in cu. ft.

P = absolute pressure in lbs. per sq. ft.

T = absolute temperature in $^\circ F.$

= temperature $^\circ F. + 460$.

$1/v$ = weight of 1 cu. ft. of air.

With the use of a different constant the formula can be used for other gases: for oxygen 48.24, for nitrogen 54.97, for hydrogen 765.71, for CO_2 35.09, for CO 55.14, and for SO_2 24.10. At other temperatures than $32^\circ F.$, the weight per

TABLE VIII

COMBUSTION DATA

In terms of lbs. per lb. of Fuel

	Molecular Symbol.	Theoretically Required. Lbs.		CO ₂	Products of Combustion. Lbs.			
		O ₂	Air.		H ₂ O	N ₂	CO	SO ₂
Carbon (to CO ₂)	C	2.667	11.52	3.667	—	8.85	—	—
Carbon (to CO)	C	1.333	5.76	—	—	4.43	2.333	—
Carbon Monoxide	CO	0.572	2.46	1.57	—	1.89	—	—
Sulphur	S	1.000	4.32	—	—	3.32	—	2.00
Hydrogen	H ₂	8.000	34.56	—	9.00	26.56	—	—
Methane	CH ₄	4.000	17.28	2.75	2.25	13.28	—	—
Acetylene	C ₂ H ₂	3.077	13.29	3.39	0.69	10.21	—	—
Ethylene	C ₂ H ₄	3.429	14.81	3.14	1.29	11.38	—	—
Ethane	C ₂ H ₆	3.733	16.13	2.93	1.80	12.40	—	—
Hydrogen Sulphide	H ₂ S	1.412	6.10	—	0.53	4.69	—	1.88

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TABLE VIIIb
COMBUSTION DATA
In terms of Cubic feet per Cubic foot of Fuel

	Molecular Symbol.	Theoretically Required. Cubic ft.		Products of Combustion. Cubic feet.				
		O ₂	Air.	CO ₂	H ₂ O	N ₂	CO	SO ₂
Carbon Monoxide	C	0.5	2.391	1	—	1.891	—	—
Hydrogen	H ₂	0.5	2.391	—	1	1.891	—	—
Methane	CH ₄	2.0	9.564	1	2	7.564	—	—
Acetylene	C ₂ H ₂	2.5	11.955	2	1	9.455	—	—
Ethylene	C ₂ H ₄	3.0	14.346	2	2	11.346	—	—
Ethane	C ₂ H ₆	3.5	16.737	2	3	13.237	—	—
Hydrogen Sulphide	H ₂ S	1.5	7.173	—	1	5.673	—	1

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cubic foot of air at barometric pressure can be found from the following formula—

$$W = .0807 \frac{492}{T},$$

where W = weight per cubic foot.

T = absolute temperature ° F.

The tables on pages 50 and 51 show the amounts of oxygen and air at 32° F. and 29.92 ins. of mercury air pressure necessary for the combustion of the elements in the coal.

The curves in Fig. 10, by the U.S. Bureau of Mines, illustrate graphically the general process of combustion in and beyond the fuel bed, the gradual consumption of the combustible gases, and the reformation of CO_2 in a properly proportioned combustion space. The diagram is a generalization of the results of many tests.

It will be clearly seen from what has been said in this section that the control of the furnace air is one of the most important factors governing efficient combustion. As already stated, the combustible constituents in coal are carbon, available hydrogen, and sulphur. With complete combustion the carbon burns to CO_2 , hydrogen burns to H_2O , and the sulphur burns to SO_2 . Only the product of combustion of carbon (CO_2) remains in the gaseous form and can thus be determined by methods of volumetric gas analysis. The product of hydrogen (H_2O) condenses and does not enter into the gas analysis. The product of combustion of sulphur (SO_2) is very small and is usually absorbed by the moisture, or by the water in the gas collecting and analysing apparatus. Thus, if coal were composed of pure carbon, with complete combustion, the products would be 21 per cent by volume of CO_2 and 79 per cent by volume of nitrogen (N). This is unobtainable in ordinary practice and the maximum CO_2 that can be obtained from a coal of known composition, completely consumed with no excess of dry air, is found as follows. Assume ultimate analysis of the dry coal to be—

Hydrogen	.	.	.	.	4.82	per cent.
Carbon	.	.	.	.	76.57	"
Nitrogen	.	.	.	.	1.55	"
Oxygen	.	.	.	.	4.99	"
Sulphur	.	.	.	.	1.41	"
Ash	.	.	.	.	10.66	"
					<hr/>	
					100.00	

$$\text{Available Hydrogen} = \left(\text{H} - \frac{\text{O}}{8} \right) = 4.2 \text{ per cent.}$$

(U.S. Bureau of Mines.)

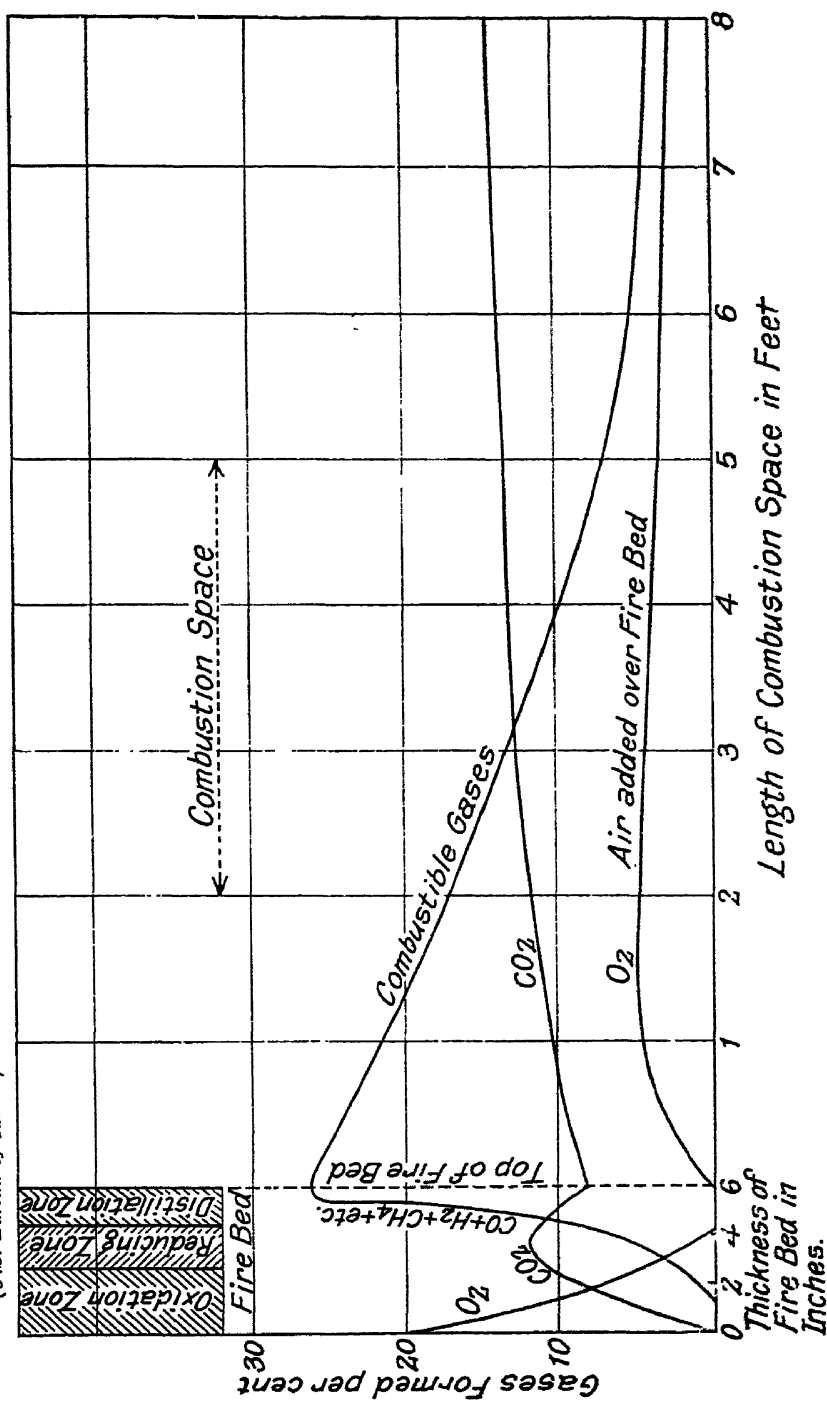


FIG. 10.

Then—

Oxygen needed to burn carbon .	0.7657×2.66	$= 2.04$ lbs.
Oxygen needed to burn available hydrogen	0.042×8	$= 0.336$ lbs.
Oxygen needed to burn sulphur .	0.014×1	$= 0.014$ lbs.
		<hr/>
		2.390 lbs.
		<hr/>

Proportion of oxygen needed to burn carbon alone $\frac{2.04}{2.39} = 0.855$.

Percentage of original oxygen in air used in burning carbon to form CO_2
 $= 0.855 \times 20.8$
 $= 17.78$.

(20.8 is actual percentage by volume of O in air.)

Then, CO_2 expressed in percentage of total gas residue

$$= \frac{17.78}{79.2 + 17.78} \times 100 = 18.3 \text{ per cent.}$$

This is the maximum percentage of CO_2 that can be obtained when completely burning, with no excess of air, the coal under consideration. For various reasons absolutely perfect combustion is impossible with the present methods of firing coal, and the air admitted is usually greatly in excess of that required. This excess air reduces the CO_2 , increases the products of combustion, and therefore reduces the efficiency. A certain excess of air, however, is necessary, partly because of the inadequate mixing of the air with the combustible and also because of the appreciable time required for combustion, which is governed by the law of mass action. For instance, if in a unit volume of gas there are two molecules of carbon monoxide (2CO) and ten molecules of oxygen (O_2), there is a greater chance of the molecules meeting and forming carbon dioxide (2CO_2) than if the unit volume of gas had only contained the one molecule of oxygen theoretically necessary for combination. In the ordinary boiler furnace, if the air supply were regulated and limited to the amount theoretically necessary for the coal being burned, the reaction would take so long with the present type of air mixing arrangements, that the gases would have passed through the furnace before being completely consumed. In practice it is found that the best results are obtained with about 40 per cent excess air. There are various methods of determining when the air supply is correctly proportioned, and these methods will be discussed later.

Furnace Control. In the previous chapter it has been seen

that perfect combustion is attained when the correct proportions of combustible and oxygen unite with each other. Modern automatic stokers are provided with the necessary means for controlling the combustible and oxidizing agents, and in most types of stoker, at present in use, the control of the process of combustion to suit the steam demand from the boiler-room is effected by varying the intensity of the draught, i.e. varying the quantity of air supplied to the furnace, and varying the speed of the grate and thickness of fire-bed. The mechanical

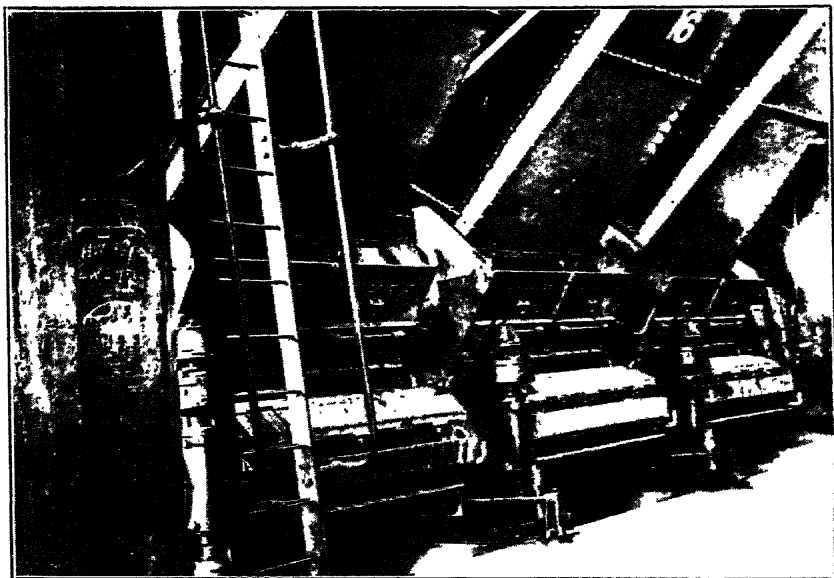


FIG. 11.—UNDERFEED STOKERS,
STANDARD "A" TRAVELLING GRATE TYPE.

stokers used in the majority of power stations can be divided into three general groups or classes, viz. chain grate or travelling grate, over-feed stokers, and under-feed stokers.

In the first class the coal is carried in a layer of even thickness on a grate in the form of an endless chain. A suitably shaped hopper at the front end of the grate holds the supply of fuel. From here the coal is fed through a door which regulates the depth of the fire-bed, it is then ignited and exposed to distillation as it is carried along beneath the ignition arch, being further consumed as it slowly travels towards the rear of the grate. The grate itself may be driven by either a small steam engine

or electric motor. The grate drive is one of the most important in the power station, and too often one finds the grates of all the boilers driven from the one motor, a breakdown of either the motor or its control gear inevitably resulting in a total shut down. Where at all possible, provision should be made for driving the grates of each boiler individually. Fig. 11 shows a stoker of this class. The grate consists of an endless chain of box-shaped fire-bars mounted upon chains, the links of which engage sprocket-wheels, which are rotated by means of the driving shaft and worm, *A* and *B*. The caps of the fire-bars are perforated or slotted for the delivery of air into the fuel-bed. The grate is composed of a number of moving box-shaped sections, which open as they pass around the rear sprocket-wheel, close again underneath, open again at the front, and finally close when passing under the feeding hopper.

The air supply for the maintenance of combustion enters through the rectangular boxes at the sides of the stokers, and flows into the longitudinal chambers on either side of the stoker. A cross-section through the grate in Fig. 11 is shown in Fig. 12. These chambers have their upper surfaces sloping at an angle of approximately 30° , and are provided with longitudinal openings *A* for the delivery of air into the open ends of the box-shaped fire-bars, which register with the top opening *A* of the air chambers *EE*. The course of the air is shown by the arrows. The louvres in the air trunks are controlled from the front of the grate, and the air can be so distributed that at the front, where the fresh coal is being fed and the resistance to the admission of air is greatest, the maximum quantity can be supplied; while at the back, where the fire is thin and sometimes open, the supply can be reduced to a minimum. This control of air distribution is one of the best features incorporated in modern stokers.

Most manufacturers now provide some such means of control, and in stations where stokers of this type are installed, there ought to be very little excuse for bad furnace conditions, providing the plant is kept in a good state of repair. The fuel is fed from a hopper in the usual way. A door or shutter at the back of the hopper is adapted for raising or lowering by rack and pinion for adjusting the thickness of the fuel-bed. In some stokers of this pattern the door is made in sections so that over the section of fire-bed the ingoing thickness can be varied. This is a necessity where a mixed fuel is being burned, owing to the tendency for the larger pieces to flow

to the sides, and on reaching the grate being consumed before that in the middle, thus leaving patchy parts on the grate through which excess air will flow and reduce the furnace efficiency. The stoker just described can be operated on either induced, forced, balanced, or natural draught, though it is designed primarily as a forced draught stoker. In the

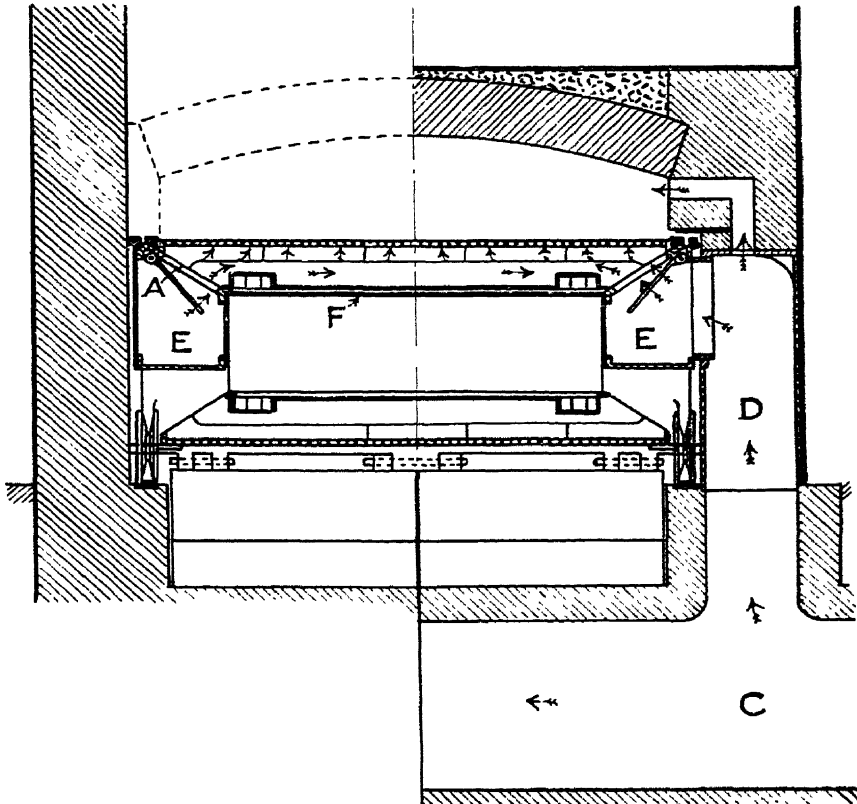


FIG. 12.—CLASS "A" TRAVELLING GRATE STOKER.
TRANSVERSE SECTION.

second class or over-feed type of stoker the grates are usually fixed, but alternate sections are subject to a reciprocating motion. The grates slope from front to rear or from the wings to the centre, and the moving parts serve to agitate and work the burning coal down to the ash receiver. This type of grate is used to a large extent in American practice, but in this country it is not used so extensively as the chain grate and under-feed type of stoker.

The principle of the under-feed type of stoker is analogous to the gas producer. Coal is fed to the lower level of the fuel-bed and by mechanical means it is gradually worked up to the surface of the fire. In doing so it is coked and gives off its volatile constituent, becoming incandescent as it reaches the top layer. Fig. 13 is a transverse section through the grate of a stoker of the under-feed type. The coal is automatically fed from a hopper into the trough above *E*. The coking process starts and as the coal rises in the trough, or coking retort, it is flooded on to the bars *F*. These bars are alternately moving and fixed, the moving bars receiving their motion from a mechanism outside the furnace.

The movement of the grates, besides carrying the fuel to

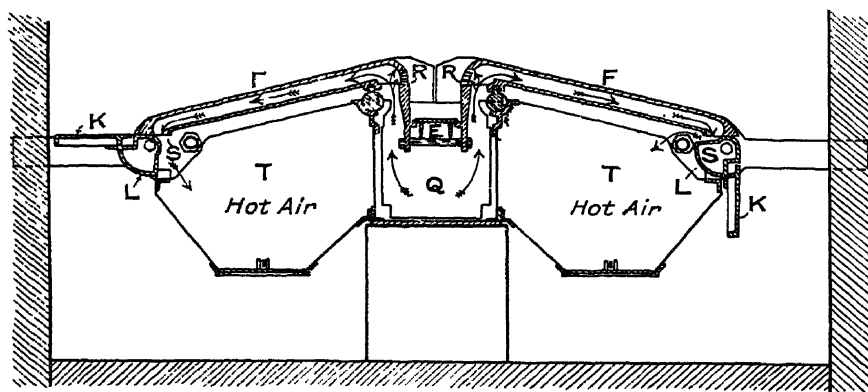


FIG. 13.—TRANSVERSE SECTION, CLASS "E" STOKER.

the sides of the furnace, also convey the clinker down and deposit it on dump plates *K*, which are hinged at *L*. One of the important features of this stoker is the distribution of the air. Upon entering the wind-box *Q* the air passes upward along each side of the trough, or retort, and is discharged partly through the holes *R* into the retort. The remaining layer passes through the bars *F*, which it will be observed are of hollow construction. These bars, however, have no openings in their top surfaces, and no air can find its way into the grate above until it has passed through the aperture *S* at the bottom end of the bar, from which aperture it is discharged into the enclosed air chambers *T*. From here the air rises and passes through the small spaces between the bars into the coked fuel. The heat, taken up by the air in passing through the bars, raises its temperature in the air chamber from 350° to 400° F.

The heat thus carried away from the fire-bars helps to keep them cool and so prolong their life. This type of stoker is also provided with small air valves at the front of the boiler, through which secondary air can be admitted to the combustion space. Opinion is divided as to the necessity of secondary air. Experiments of the Bureau of Mines, America, prove, it is claimed, that not over 50 per cent of the air required for the complete combustion of coal can come through an incandescent fuel-bed free from holes, and that the remainder must be introduced above the bed, unless it creeps through unignited fuel or through holes in the fire. There are, of course, many other types of stokers in use besides those of the type described, but those chosen for the purpose of illustration serve to show how the process of combustion is carried out in the automatic or mechanical type of stoker.

The use of pulverized coal is the greatest advance we have made in methods of burning coal. The types of mechanical stoker just described are, up to the normal full load of the boiler, eminently efficient if intelligently operated, but at high overloads, especially if sustained for any considerable time, the accumulation of clinker and the overheating, due to the excessive furnace temperatures, results in damage to the grate, and the coal consumption is very uneconomical. With pulverized coal as fuel the boiler can be kept at maximum duty for long periods.

Banking losses are also eliminated, and in plants in which this type of plant is installed it has been found that, after stopping the fuel-feed and closing the flue damper, the steam gauge only showed a drop in pressure of a few pounds. The heat in the furnace lining, etc., being sufficient to hold the pressure over a considerable period of hours. Tests on a large American plant showed that a high CO_2 was easily obtainable, but often at the expense of the furnace linings, excess air having to be admitted to keep the flame temperature to $3,000^\circ\text{F.}$ and the refractories to $2,500^\circ\text{F.}$ An overall boiler house thermal efficiency of 90 per cent is claimed to have been obtained. A detailed description of this system is outside the scope of this book, but briefly it essentially consists of a plant in which the coal is pulverized to a degree that 85 per cent of the coal powder will pass through a 200-mesh screen, i.e. 40,000 holes to the square inch. The system lends itself to very accurate air regulation and only about 20 per cent excess air is necessary for complete combustion. The coal

powder is also more readily combined with the theoretical quantity of air required for combustion than is the coal on the surface of the ordinary grate. Ignition takes place instantaneously upon emergence of the coal-dust from the burner nozzle, every particle being completely consumed.

Another important point in connection with the combustion of fuel is the selection of firebricks, fireclay, and other refractory material for the lining of the combustion space and the construction of the ignition arch. The class of brick used should be that which has been found to give the best results with the class of fuel used, and the brick setting should be done with fireclay from the same clay pits as the bricks themselves. Often good bricks become friable in use owing to being subjected to extremes of temperature and the variation of other furnace conditions. Rapid inrushes of cold air to the furnace or combustion space should always be avoided when the boiler is on load, and care should be especially taken in clearing ashes where the open ash-pit doors are immediately below the dumping gear.

Brick-work ignition arches must be thoroughly dried out when it has been found necessary to renew them, and before the arch is subjected to the intense heat of the furnace a slow fire should be kindled beneath the arch and the drying process carried out gradually. Many arch failures are not due to an inferior quality of brick, but entirely to the heating and drying being too rapidly carried out.

Artificial draught owing to its greater efficiency is employed on all modern power station boiler units, but some of the older and smaller stations are dependent entirely upon natural draught. In these plants the installation of a fan would help considerably towards increased efficiency and boiler capacity. The choice of a draught system is settled by the designers of the plant and depends upon grate area, type of boiler, and the class of coal which will be burned. Induced draught, which is the type most frequently used in power station work, is all that is necessary to burn coal of average quality, and where ample fan-power is provided this system will fill all requirements. Where the boiler and the economizer setting is of brick, and not carefully looked after and periodically pointed, an appreciable loss can occur with this draught system due to the infiltration of cold air through the leaky brick-work. Where a low grade, poor quality, or anthracite fuel is to be burned, and where heavy fires have to

be carried and rapid rates of combustion obtained, forced draught is necessary; induced draught being unable to maintain the high air pressure beneath the grate necessary for burning these qualities of fuel.

With either type of artificial draught care must be taken in making adjustments of the intensity of the draught, otherwise, if it is allowed to become excessive, the lighter partly-burned fuel will be lifted or blown from the grate, leaving

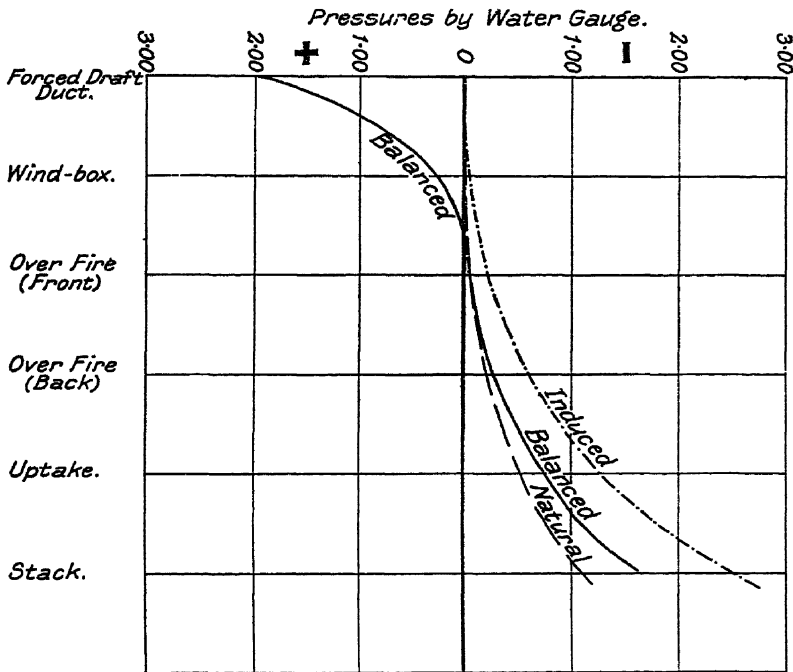


FIG. 14.—DRAUGHT SYSTEMS.

bare patches through which excess air will enter. In many of the power stations recently erected both systems of producing artificial draught have been installed, and a system defined as balanced draught has been recommended by various boiler and combustion authorities. Briefly, it consists of running both forced and induced draught fans so that the pressure in the wind-box below the grate is just sufficient to overcome the resistance of the fire-bed, the damper, or motor speed of the induced draught fan being so regulated that the depression of pressure in the uptake will be just sufficient to lift the products of combustion from the surface of the fire-bed through the

gas passes of the boiler, approximately atmospheric pressure being maintained at the fire-door. Where only forced draught fans are installed the same conditions can be set by adjustment of the stack damper and air pressure in the forced draught duct. Fig. 14 shows graphically the various systems of draught.

The heat generated in the furnace is transferred to the water in the boiler in three different ways, viz. by radiation, in which

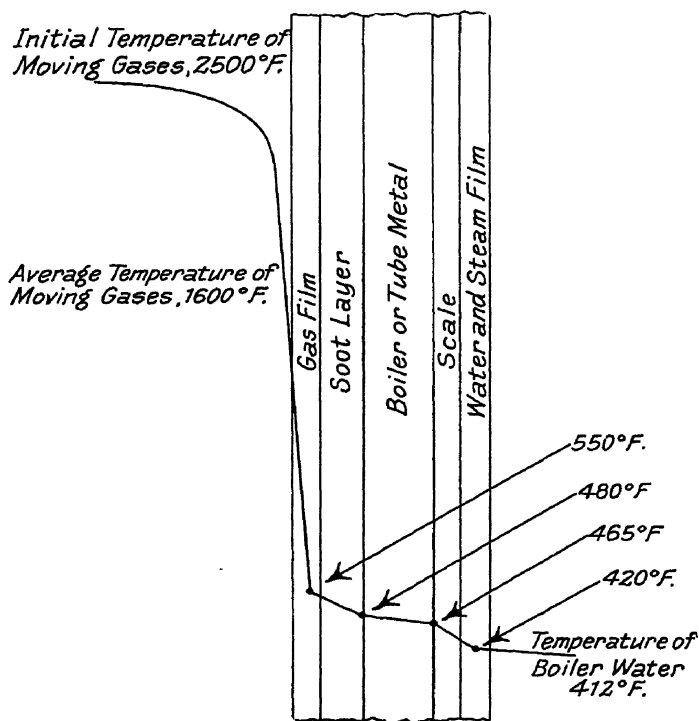


FIG. 15.—HEAT TRANSMISSION BY CONDUCTION AND CONVECTION.

Adapted from diagram by U.S. Bureau of Mines.

some of the heat is radiated directly from the incandescent fire-bed and luminous gases to the boiler tubes or plates; by convection in which heat is transferred to the heating surfaces by the ascending particles of gas, the cooled particles of gas next to the heat absorbing surfaces being continually replaced by the hotter particles, due to the movement of the gases; by conduction, in which the heat of the gases is conveyed to the water by way of the tube materials and soot and scale layers. The heat absorbed is finally distributed throughout the water in the boiler almost entirely by convection. Fig. 15,

U.S. Bureau of Mines, represents diagrammatically, but not to scale, the temperature drop of the gases across the boiler plate or tube plate, and encrustants to the water. In the past, weight has formed the basis of comparison of furnace and boiler performance. It was customary to compare boiler performance on a basis of the equivalent evaporation of so many pounds of water per pound of coal, from and at 212° F. The consumption of so many pounds of coal per square foot of grate area per hour formed the basis upon which the performance of stokers was compared. It is now recognized that comparisons made by these methods were unfair. In the case of furnace performance, it is the amount of heat units liberated that is the criterion, and in order to make allowance for the different qualities of coal, a method of comparison based on heat liberation per square foot of grate area was proposed, and this method is now in use in a few of the larger central stations. (*Steam Raising*, by D. Wilson. I.M.E.A. annual meeting, 20th to 22nd July, 1921.) At that meeting it was stated that it doesn't pay owing to increased maintenance costs, as the results of high rates of consumption, to exceed 350,000 B.T.U.'s per square foot per hour as a maximum for normal duty.

Not only stoker performance but all boiler-room plant performance should be expressed as far as possible in B.T.U.'s.

The figure adopted in this country as the normal figure for heat transference is 7,000 B.T.U.'s per hour per square foot of heating surface. The limit of heat transmission, however, through the heating surface of a water-tube boiler has not been arrived at, the practical difficulty of burning the fuel being reached long before there is any detrimental effect on the heating surface. Experiments have shown that it is possible to obtain an evaporation rate equal to a heat transmission rate of 140,000 B.T.U.'s per square foot of heating surface per hour without detrimental effects. Clean heating surfaces are essential to high boiler efficiency. The maximum period that a large steaming unit can remain in operation is fixed by the condition of the tubes and heating surfaces, and the efficiency of the unit in operation will fall away as the heat absorption rate becomes impaired, due to the clogged tube spaces and encrustation on the heating surfaces. The cost of periodically cleaning a boiler externally is a serious item in a large plant, and some system of cleaning the heating surfaces and tube passages, while the boiler is in operation, is essential if the efficiency of the unit is to be maintained from day to

day. The old system of using a steam lance while the boiler was kept on the range has been dispensed with in modern plants, and a fixed type of lance is now very often installed ; one in each gas pass and other important points in the boiler. The Diamond soot-blower is typical of this new type, and from tests carried out by the author the conclusion come to is, that their adoption in plants of any considerable size would be justified by the saving effected due to their use. Not only is there a saving due to the efficiency of the boiler being maintained for long periods, but there is also the saving due to the fact that operation of the soot-blowers does not require the shutting down of the boiler. In order to clean a large boiler externally by hand, it is necessary to shut down the boiler for a considerable period, usually over a week-end, during which time the boiler setting, etc., cools and has to be warmed up again. The soot-blower, if properly installed, also makes a more efficient job of the cleaning than is done by manual labour. The percentage gain in efficiency of boiler and furnace due to soot-blowers is in the neighbourhood of 2 to 3 per cent. The type of soot-blower referred to is made with a movable head, so that the lance and jets can be rotated through a previously determined angle. By doing so, all danger of tube trouble, due to the steam jet always impinging on the same point, is eliminated. A large modern water-tube boiler unit, fitted with seven sets of soot-blowers on either side, can be efficiently cleaned in less than a quarter of an hour, for an expenditure of from 600 to 700 lbs. of steam.

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CHAPTER IV

BOILER-ROOM MEASUREMENTS

THE generation of steam from water is always attended by considerable loss, but using a good coal on a modern boiler unit a combined efficiency of boiler, superheater, and economizer equal to 85 per cent of the heat value of the fuel is well within our reach under test conditions, and in a modern plant it should be quite possible to maintain a daily working efficiency of 75 to 80 per cent. One of the first requisites in improving or maintaining efficient boiler-room practice is a record of performance, with an efficient system of tabulation and investigation of the records obtained. It is essential that the water evaporated should be measured and the coal consumption accurately determined. In fact, if the plant is of any size at all, each boiler unit ought to be equipped, in addition to the usual mountings, with accurate steam flow meters, thermometers, and pyrometers for steam and flue-gas temperatures, draught gauges, and a reliable CO₂ recorder. These instruments as far as possible, should be mounted on a panel in front, or at the side of the boiler about five or six feet above the level of the firing floor. In this position they are then under the constant observation of the boiler-room engineer-in-charge. Though the importance of accurate records of plant performance is now universally recognized as essential for maximum economy, it is a sad admission that the majority of power stations have no real system of recording and tabulating results. In many of the plants which do have some sort of a system, the lack of interest on the part of the engineers usually results in the records of the day's operation being filed away without being looked at. As a rule, in most stations, the records for the day's running are worked out by the engineers on night shift. This should not be so, for to accurately work out the operating results of even the boiler house is a long job, and if left to the night shift engineers, their attention is taken off the routine operation of the plant. Accurate record keeping and supervision of efficiency control in even a small station requires more time than the average shift engineer has at his disposal. In the case of the small station the calculations should be done by the station or boiler house superintendent,

or an assistant, and in the case of the larger undertakings, this work should be carried out by the staff of a power stations' tests engineer. The shift engineer has thus only to see that readings are carefully taken and entered in the log sheets. A summary of each day's operation, showing the various efficiencies and losses, should be kept by the shift engineers, the information being supplied to them from the department responsible for the calculation of the operating records. If the staff is to operate the plant at its maximum efficiency it is essential that they should be in possession of accurate data, showing what results can be obtained from the plant in first-class condition. Failing the possession of such data they are to a large extent working in the dark, and cannot judge whether the results being obtained are the best possible or not.

In certain plants, however, record keeping is overdone and it is in these plants that the whole business becomes merely a matter of routine, and the interest of the engineers is gradually lost, the work of entering the records becoming purely mechanical. Others, again, are content if an approximate value of the efficiency figure is obtained, no thought being given to the separation of the various losses and whether they are being kept to as low a value as they could be. No system of record keeping can be instituted or successfully carried on without the use of instruments. Instruments are not installed in the boiler-room to "show up" the boiler-room crew, and the men ought to be taught that the instruments are not scientific toys, but tools, enabling fuel and equipment to be used more economically and advantageously, and without which no conscientious or trained fireman can do his work. To work efficiently and successfully one must know what is required to be done, whether it is being done, and how it is being done. Boiler-room instruments can supply all that information, and if intelligently used are a boon to the user and result in a saving of money and needless effort on the part of the fireman. In certain cases the lack of instruments in the plant is entirely due to the conservative ideas held by directors or council members, who will not sanction the capital outlay involved in the purchase of the necessary apparatus. Such people require a great deal of conversion to realize that the return on the outlay, due to the increased efficiency obtained by the intelligent use of instruments, will not only very soon pay for their installation, but result in a substantial

saving as well. One comparatively small corporation undertaking, after an expenditure of £200 on scientific boiler-room instruments, was able to report a saving of 1,900 tons of coal, representing at the price then obtaining £3,000 on the fuel bill. This is all the more worthy of note since the station referred to had always produced very low fuel costs. A point often overlooked, when instruments are installed, is that the engineer expects them to go on working without attention. The instrument has yet to be invented which will fulfil this ideal, and all the instruments on the turbine and boiler-room side of the station should be kept in a high state of repair by a capable man, who can do for the mechanical instruments what the electrical laboratory do for the power meters.

The Measurement of Coal. In many modern stations it has not been thought necessary to install automatic coal weighing machines, but without them or some equivalent, no quick or accurate method of obtaining efficiency figures over short periods is available. Under modern boiler-room conditions, where the closest supervision of the burning of fuel is imperative, the author is of the opinion that money expended on these appliances is well spent. The method adopted for the measurement of coal in the boiler-room depends upon the method of coal handling. Most modern plants at least weigh their coal as it is delivered in the wagons, but this method gives no indication of the daily coal consumption, and if a boiler-room is to be efficiently operated it is imperative, not only to know the daily coal consumption, but also the consumption for each boiler unit for any period.

The "Avery" Coal-weighing Machine. There are two general methods by which coal measurement can be effected automatically: direct weighing; and measurement by volume. The direct weighing type of apparatus essentially consists of automatic scales, the hoppers of which are arranged so that the supply is shut off as soon as the hoppers are filled to a predetermined weight, after which the hopper discharges and is reset automatically. Each hopper load is recorded on an integrator operated by the tipping mechanism. Those made by Messrs. Avery are typical of this class and are very accurate in operation. Tests carried out from time to time by the author on an installation of these automatic weighers showed the greatest error to be plus or minus 1 lb. in 224 lbs. Fig. 16 shows the Avery coal-weighing machines in one of the boiler-rooms at Dalmarnock Power Station. Where at all possible

a separate weighing machine should be installed at the top of each coal chute leading to the stoker hoppers, but where this is impracticable a coal-weighing and hopper-charging apparatus, arranged on overhead rails to run the length of the firing floor, should be installed. Such a system is not suitable for the larger power stations, owing to the enormous quantity of coal to be handled.

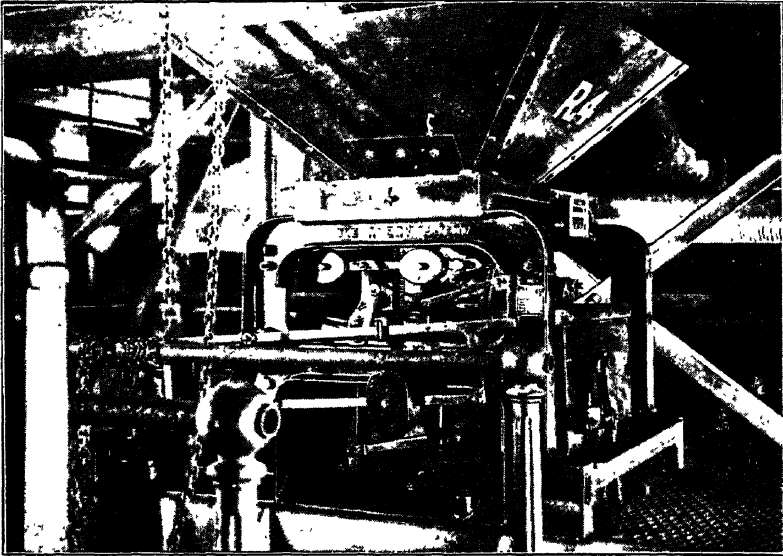


FIG. 16.—“AVERY” AUTOMATIC COAL-WEIGHING MACHINE.

The “Lea” Coal Meter. The best example of a machine of the second type, namely, those in which the coal is measured by volume, is that made by the Lea Recorder Co. This machine is simply a special adaptation of the Lea water meter and recorder, with which most power station engineers are familiar. Its action is based on the theory that when coal is supplied to a boiler by means of a chain-grate stoker, the amount of fuel passing under the fire-door may be regarded as a stream, with a constant width, but variable in depth and velocity. The width of the stream is the width of the chain-grate, the depth is the thickness of the fire, and the speed is the rate of travel of the chain-grate. Although slack and small coal do not obey the laws of fluids or mathematics exactly, it has been found by experience that under ordinary conditions of working, the flow of coal under a fire-door is,

generally speaking, proportional to the thickness of the fire and to the velocity of the grate, and the results are very consistent with what might be expected theoretically. The apparatus occupies very little space and the makers give a guarantee of accuracy to within 2 per cent. Fig. 17 shows diagrammatically the principle of operation.

A very simple and inexpensive type of instrument for the volumetric measurement of coal is that made by Messrs. Geo. Kent, Ltd.

The meter is designed to measure the volume of coal or

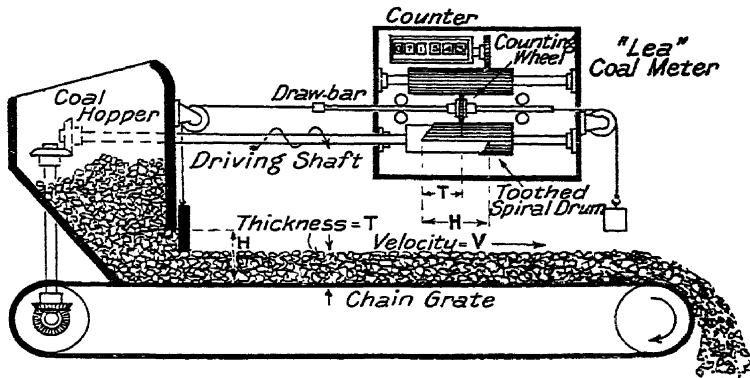


FIG. 17.—DIAGRAMMATIC VIEW OF "LEA" COAL METER.
(Not to scale).

other granular material passing down through a vertical chute. The best results are obtained on small chutes of circular form, and the instrument should be installed so that there are at least two diameters of parallel piping above and below the helix of the meter.

The meter, which has an advantage of taking up only a small amount of room, consists of a helix or propeller connected by means of a flexible shaft to a train of integrating gears provided with recording dials housed in a cast-iron casing.

The casing containing the integrating mechanism is bolted to the outside of the chute, the helix being suspended in the chute through which the material descends, and by its revolutions communicated to the counting mechanism, shows the volume passing.

The reading on the dials is in terms of cubic feet of coal passing down the chute, and to obtain the weight of coal passing it is necessary to multiply the counter readings by the weight per cubic foot of the coal being measured.

In plants where no coal weighing apparatus is installed, the engineer-in-charge is seriously handicapped as far as a knowledge of the performance of his plant is concerned. There are many ways, however, by which the approximate consumption of the boiler furnaces can be arrived at, and even the consumption for a single unit in some cases presents very little difficulty. Where the boilers are fitted with chain-grates the solution to the problem is fairly easily carried out by accurately adjusting the fire-door to coincide with the height in inches indicated by the pointer on the front of the stoker, ascertaining the speed of the grate in feet per hour, and instituting a small log sheet on which the fireman can record the times, changes in grate speed, and fire-bed thickness. All this will require a little extra exertion on the part of those concerned, but this will be a secondary consideration to the engineer desirous of improving the operation of the plant. Where it is impracticable to measure the coal in the manner described, but where the bunkers or silos are overhead, another method can be adopted. The volume of the bunker or silo should be determined, and a scale drawn up, giving the weights of coal in the bunker at different levels. Periods can then be fixed at which the coal in each bunker is levelled and checked off on the diagram. Readings would also be taken in a similar manner of the coal filled in. There is, of course, the objection that coal may be being drawn from the bunker at the same time as it is being filled, but these periods could be arranged so that they do not overlap. Other approximate methods of determining the coal consumption will no doubt, from the examples given here, suggest themselves to the keen engineer, and while not being strictly accurate, they will at least be approximately comparative.

The Measurement of Steam. In boiler house efficiency control it is essential that the water evaporated be known to as accurate a degree as possible. This can be accomplished by measuring the turbine condensate, and metering the make-up feed-water, but this gives no indication of the steam output from the individual boiler units. For this latter measurement a steam flow meter is necessary. With the present types of steam flow meters an accuracy of plus or minus 2 per cent can be obtained under ordinary operating conditions. The present-day steam flow meters consist broadly of two classes: those in which a meter operates on the difference of pressure set up on two sides of a throttle disc inserted in the steam

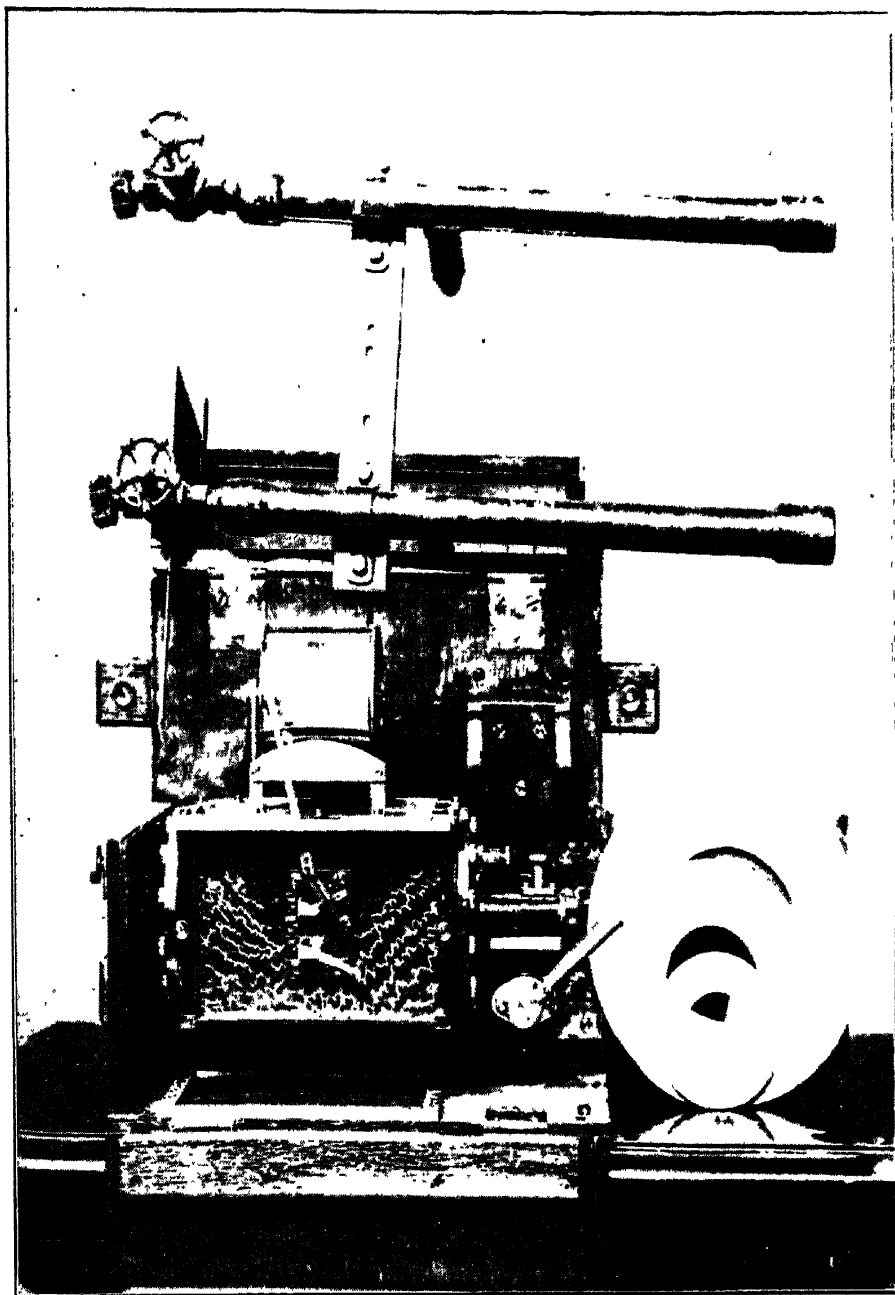


FIG. 18.—“KENT” PORTABLE STEAM METER.

flow, and those operating on the Pitot tube principle. Very accurate instruments representative of the first-named type have been developed by Messrs. Kent, who give a guarantee of plus or minus 2 per cent from three-quarters to full load for one of their latest instruments. A portable Kent meter, with a set of orifice plates to work at different steam velocities, should be in the possession of the tests department of every large undertaking. Such an instrument is invaluable when

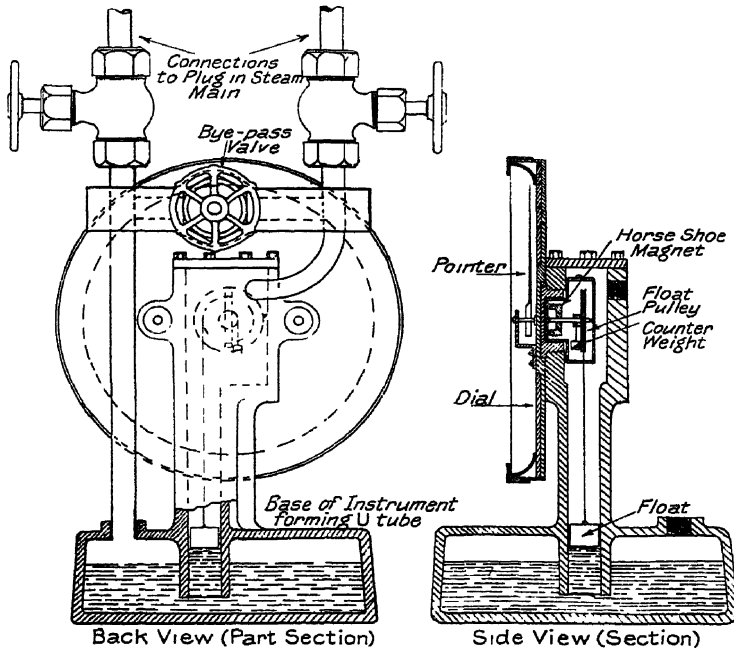


FIG. 19.—“B.T.H.” STEAM FLOW METER.

measuring the steam consumptions of auxiliaries and other plant not provided with metering apparatus. Fig. 18 is a photograph of the instrument referred to.

Another well-known steam flow meter is that made by the British Thomson-Houston Co. An installation of B.T.H. steam flow meters is shown in the boiler-room in Fig. 7, and a diagrammatic view of the instrument in Fig. 19. The Pitot tube is adopted in this type; the Pitot tube proper consists of a plug which is inserted into the steam main: this plug has a set of holes facing the flow of the steam, and an internal tube brought out to the opposite side of the plug forms the trailing hole. The recorder or indicator is connected to the

inner and outer portions of this plug by means of two tubes, valves being provided for shutting down the instrument when in need of adjustment. The indicator is practically a U-tube, the working fluid being mercury: the movement of the indicating mechanism in the inner chamber being communicated to the dial pointer by means of a horse-shoe magnet. In both types of flow meters described, it is necessary that the connecting pipes between the indicator and orifice plate, or Pitot tube, be kept full of water. The condensation of the steam usually provides this, extra radiating surface being provided near the orifice plate or Pitot tube to ensure a constant supply of water. The piping system, etc., must be kept free from bubbles of air, otherwise erroneous readings will result. The Pitot-tube type of instrument can be equally well used for measuring either water or air, and condensing plants are now sometimes equipped with a flow meter for measuring the quantity of circulating water. A recent development of the B.T.H. flow meter is shown in Figs. 19 (A) and (B). In this instrument a combination of indicating, recording, and integrating mechanism is accommodated in the one case, and in some instances provision is also made for the indication and recording of pressures and temperatures.

The dial of the instrument is of large diameter, the scale showing rates of flow having figures $\frac{5}{8}$ in. in height. As the dial is thus large and conspicuous, it is easily read and readily observable at a considerable distance.

The body of the meter consists of an iron casting so designed as to form a U-tube (*see* section of instrument, Fig. 19 (A)). A flow nozzle fitted in the steam main is used in conjunction with the instrument. A difference of pressure in the flow nozzle or orifice tube, caused by the flow, is transmitted to the U-tube system of the meter, and causes the mercury to fall in the chamber of the U-tube which contains the float (29) and rise in the other chamber. The magnet (27) inside the body of the instrument is rotated through an angle proportional to the change of level of the mercury, the motion of the float being transmitted to the magnet by means of a rack and pinion.

The motion of this magnet is transmitted magnetically to another magnet (13), which operates the indicating pointer (3), recording pen (11), and the integrating mechanism (18).

With all types of flow meters, whether used for steam, water, air, or gas, it ought to be borne in mind that accurate

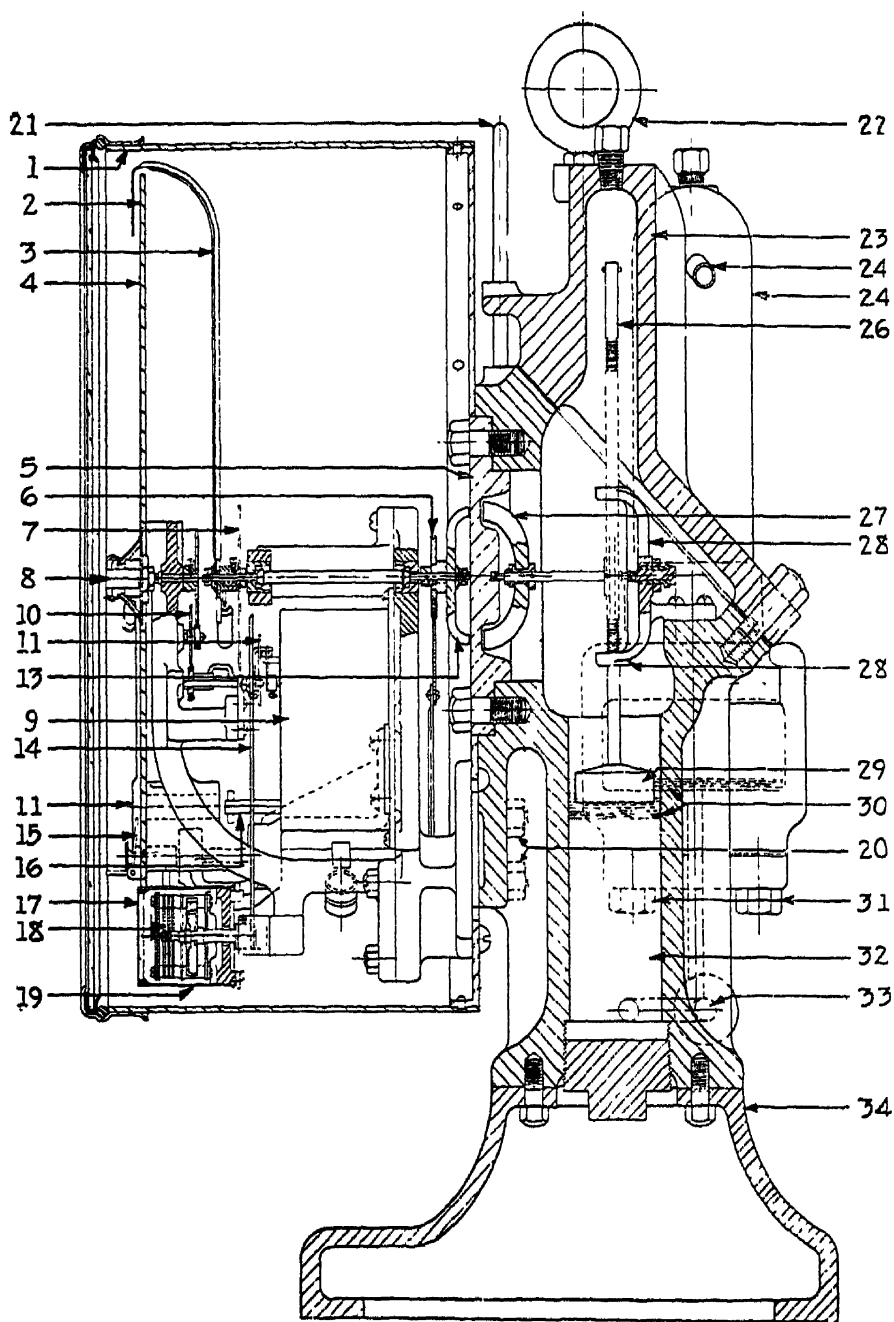


FIG. 19 (A).

measurements will not be obtained if the flow of fluid or gas passing the measuring nozzle, orifice tube, or Pitot tube is of a pulsating nature.

Before leaving the subject of steam measurements, mention must be made of the "Alba" flow meter. The principle of operation is similar to those instruments described which utilize the difference in pressure across a nozzle or orifice plate

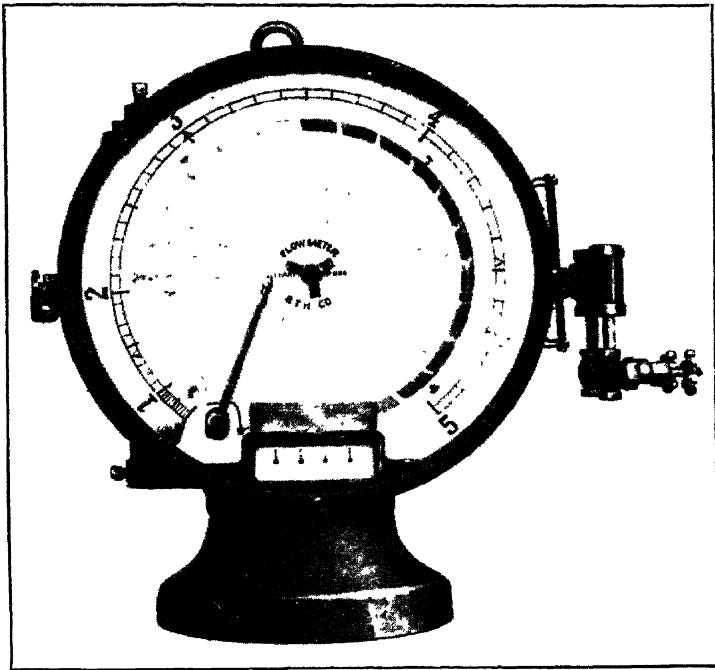


FIG. 19 (B).

for the measurement of the quantity of steam passing in the pipe in which the nozzle or orifice plate is inserted.

As stated previously, the difference between the two pressures is proportional to the quantity of steam passing, and may be read directly by the rise or fall of a column of mercury in the glass tube of a manometer.

In the simplest form of the "Alba" flow meter, the indications of the instrument are read from a scale, graduated in pounds of steam per hour, attached to the glass tube of the manometer.

An interesting development of this flow meter consists of

the recording of steam weight by means of an electric meter, which together with the necessary regulating appliances are mounted on a switchboard erected at the most convenient point. In this instance the manometer tube is fitted with platinum contacts, sealed into the side of the glass and each connected to a calibrated resistance. Current is supplied from any convenient source of constant voltage. The rising or falling of the mercury in the manometer short-circuits certain of the platinum contacts, thus inserting a greater or lesser resistance into the electrical circuit, varying the current and consequently the registering speed of the meter. In place of an integrating instrument a recording ammeter can be used, the record of steam flow being made on a chart from which the weight of steam can be calculated by means of a planimeter. The measurement of steam will be further referred to when considering turbine-room performance. The measurement of steam pressure needs no description, as all engineers are familiar with the usual types of steam pressure gauges. These should be periodically calibrated, for a gauge reading low is the cause of a great amount of unnecessary blowing off with a consequent loss of steam and coal.

The Measurement of Water. The most accurate method of determining water quantities is by direct weighing in tanks, mounted on carefully calibrated weigh bridges, arrangements being made by a system of quick change-over valves for filling one tank while the other is being weighed and emptied. To secure an uninterrupted flow of water three tanks are necessary.

For ordinary operating practice such a system is impracticable, but for test purposes on boilers and turbines this system, in the hands of a careful operator, gives results to a close degree of accuracy. The large units now being installed make direct weighing a difficult proposition, owing to the large quantities of condensate or feed-water to be handled, and in some cases permanent test tanks with the necessary piping are installed. A gauge glass is fitted the entire height of each tank in conjunction with a scale giving the height of the water and the equivalent weight in pounds.

One of the best known instruments for the measurement of water is the Lea Recorder. These instruments if carefully looked after and properly adjusted in the first place will give very reliable service. They use a V-notch measuring tank with suitable recording mechanism operated by a float.

In many power stations it is unnecessary to measure the

water in the boiler-room. If the turbine-room plant is fitted with "Lea" recorders, or other meters for measuring turbine condensate, and a small meter on the make-up system, the total water fed to and evaporated from the boilers can be arrived at from the information given from these sources. From this it must not be inferred that steam flow meters on each boiler unit are unnecessary. On small plants, and especially in the older stations where no provision is made for metering the condensate, a reliable meter for the measurement of feed water is an absolute necessity if improved results are to be looked for in the boiler-room. Improved results cannot be obtained unless the state of the plant is determined to begin with, and a knowledge of the evaporation is one of the first necessities. From this knowledge the quality of the coal can be ascertained, and the amount of steam produced per pound of coal. An increase in steam consumption can be at once detected and investigated, and the knowledge of evaporation also shows up the state of the heating surfaces as regards cleanliness, and the efficiency of the methods of firing adopted by the various shifts of firemen. Apart from the "Lea" recorder, and the other types of meter which operate on the flow of water over a V-notch or other type of weir, there are two classes of meters employed in boiler-room work. These are positive type meters and motor meters. The positive type measures every drop of water passed through it, by the driving action of the water itself upon a reciprocating piston. Probably the best known meter of this type is the Kennedy meter, which is too well known to require a detailed description.

Briefly, it consists of a piston working in a cylinder which forms the base of the meter: this cylinder is the measuring cylinder, and the indicating mechanism measures the length of the stroke, and not the number of reciprocations. This point is worthy of note since the travel of the piston varies with the speed of working. The counting gear is arranged to work in the same direction on either the upward or downward stroke of the piston-rod by means of a double ratchet and pawl-wheel which forms part of the counting mechanism. The valve motion, which throws over a reversing cock, is operated by a vertical spindle. Leaky stuffing glands do not affect the accuracy of this type of meter, but the piston rings, if not periodically examined, will eventually lead to inaccuracy in registration. Boiler-room efficiency figures are usually

calculated in the first place to a basis of weight therefore, since this type of meter measures water by volume, it is necessary to apply a temperature correction to convert to pounds. (See Table IX.)

The "Kennedy" hot-water meter has been widely adopted for measuring boiler feed-water. It is of very robust construction and seldom gives trouble. For test purposes on individual boiler units in large plants a meter of this description is a useful adjunct to the test equipment. The feed ranges in most large plants are invariably in duplicate, and the test meter can be permanently fitted in one of these ranges. It is then quite a simple matter for the boiler or boilers on test to be fed from the range in which the meter is inserted. A Kennedy meter is shown in section in Fig. 20 (p. 80).

The general principle of the motor type of meter is that the water is guided into the vanes of a little turbine, anemometer, Barker's mill or other type of small motor which will move with the stream with very little slip. The spindle of the motor is connected to a train of integrating gears which operate pointers on the dials of the meter. Some of these small motor meters give very accurate results and can be put to good use in power station work in the measurement of make-up feed-water, turbine gland sealing water, air pump sealing tank water, and water services to oil coolers. Fig. 21 shows a small "Leeds" meter installed for measuring the make-up feed-water of a large power station.

Before leaving the subject of water measurement mention must be made of the Venturi meter. This type of instrument consists of two parts, the Venturi tube and the indicating gear. The Venturi tube forms part of the pipe-line carrying the water being measured, and is made in the form of a long convergent divergent nozzle, Fig. 22. The narrowest portion is termed the throat, and if a differential gauge or U-tube be connected with one leg to the throat, and the other leg to the larger bore on the side from which the water is flowing, a difference in pressure will be indicated by the difference of level of the mercury in the gauge, and this difference will be a measure of the flow of water in the pipe.

In the type of this meter made by Messrs. Kent, the indicating apparatus consists of a mercury-filled cast-iron U-tube with connections to the throat and larger bore of the Venturi tube. A recorder is operated by a float in the mercury, and in a somewhat similar method to the "Lea" recorder,

TABLE IX

PROPERTIES OF WATER AT VARIOUS TEMPERATURES

From *Useful Tables for Engineers*, reproduced by permission of Messrs. Babcock & Wilcox, Ltd.

Temp. ° F.	B.T.U. per lb.	Weight per cubic foot. lbs.	Weight per Gallon. lbs.	Temp. ° F.	B.T.U. per lb.	Weight per cubic foot. lbs.	Weight per Gallon. lbs.
32	0.00	62.42	10.0104	125	93.10	61.65	9.887
35	3.02	62.42	10.0104	130	98.14	61.56	9.873
40	8.06	62.42	10.0104	135	103.18	61.47	9.858
45	13.08	62.42	10.0104	140	108.22	61.37	9.842
50	18.10	62.41	10.0090	145	113.26	61.28	9.828
55	23.11	62.39	10.0080	150	118.30	61.18	9.812
60	28.12	62.37	10.0025	155	123.34	61.08	9.796
65	33.12	62.35	9.998	160	128.38	60.98	9.780
70	38.11	62.31	9.993	165	133.42	60.87	9.762
75	43.11	62.27	9.986	170	138.46	60.77	9.746
80	48.09	62.23	9.980	175	143.50	60.66	9.728
85	53.07	62.18	9.972	180	148.54	60.55	9.711
90	58.04	62.13	9.964	185	153.58	60.44	9.693
95	63.02	62.08	9.956	190	158.62	60.32	9.674
100	68.01	62.02	9.946	195	163.66	60.20	9.654
105	73.00	61.96	9.937	200	168.70	60.07	9.634
110	78.00	61.89	9.926	205	173.74	59.95	9.614
115	83.02	61.82	9.914	210	178.78	59.82	9.594
120	88.06	61.74	9.901	212	180.79	59.76	9.584

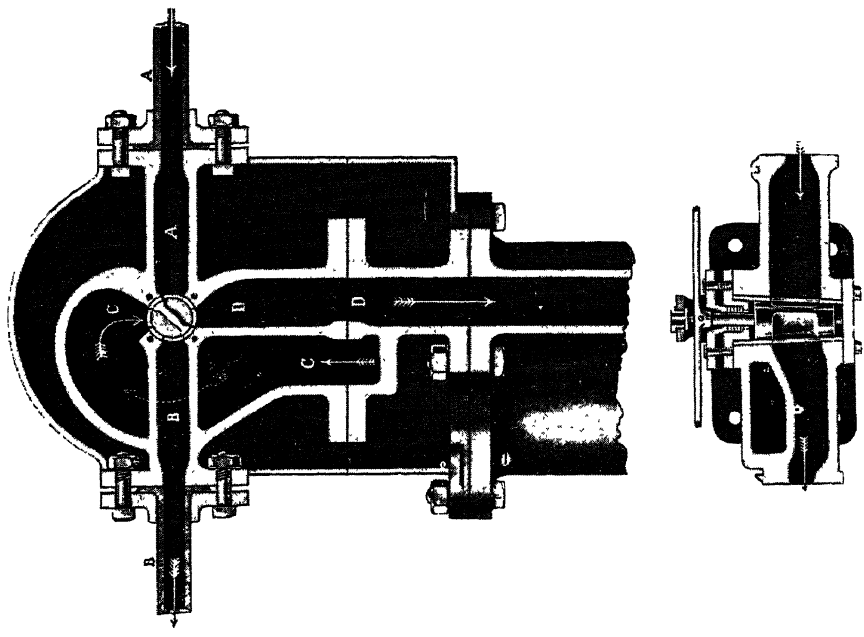
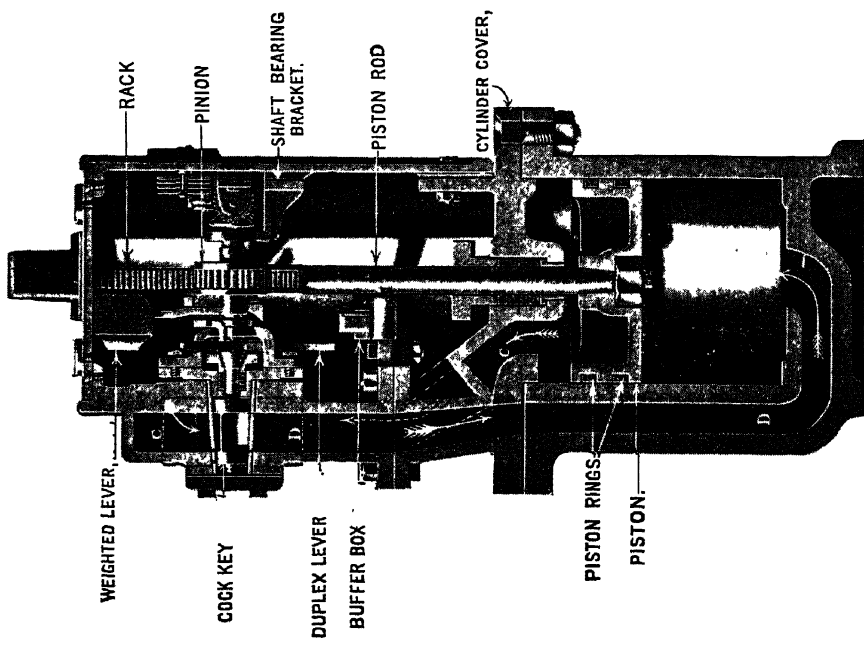


FIG. 20.

integrating or counting mechanism is operated. The meter registers in gallons and a correction has to be applied for temperature to obtain the indication in pounds, but where the water being handled does not vary in temperature to a great extent, the meter when first erected can be calibrated for the average temperature likely to be met with. The

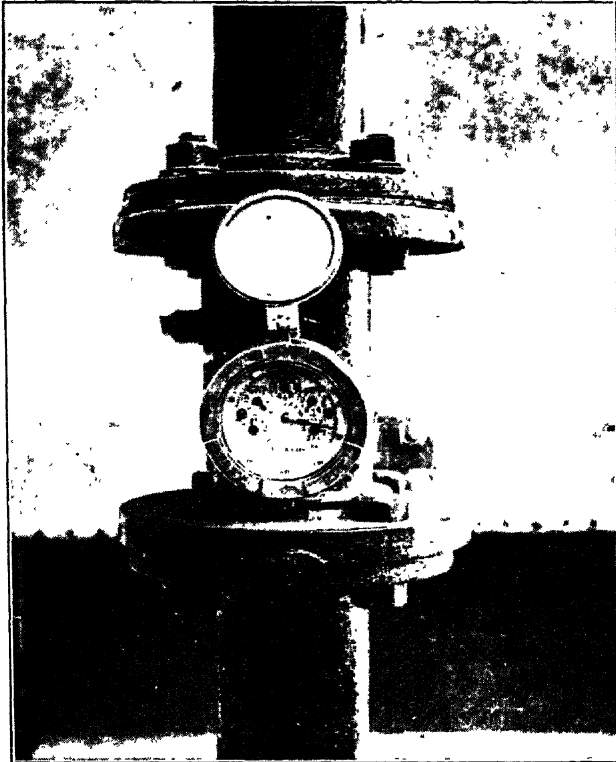


FIG. 21.—“LEEDS” METER ON MAKE-UP
FEED-WATER SYSTEM.

recorder of this type of meter need not be erected beside the Venturi tube, and can therefore be installed in any convenient position in the station up to within 1,000 ft. from the tube. Another great advantage is that one indicator can be used on one of any number of tubes. Thus, for boiler tests where it is impossible to weigh or otherwise measure the water, a Venturi tube could be installed in the feed-line to each boiler, the connections from each Venturi tube being carried to the one indicator. To connect the instrument for boiler test

purposes would then only necessitate opening the valves of the Venturi tube concerned.

Many engineers in power stations, suffering from a lack of instruments, seem unaware of the information that can be gained from the use of "home-made" Pitot and Venturi tubes. These simple pieces of apparatus can be made very cheaply and can be put to a hundred and one uses in making measurements of fluids and gases. The Pitot tubes can be made from two different diameters of tubing, the outer containing the leading holes and the inner forming the trailing

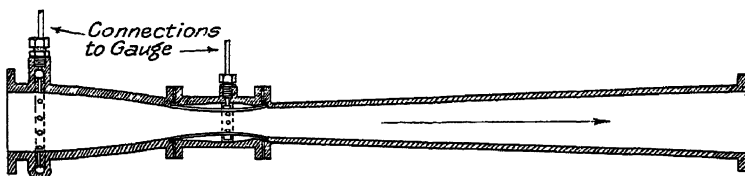


FIG. 22.—VENTURI TUBE.

hole. Small Venturi tubes can be made from brass rod or other metal, and should be so constructed that they can be supported inside the pipe by the connections to the throat and upstream side of the nozzle. The connections from the Pitot tube or Venturi nozzle can be connected to the legs of a differential gauge, and as in the case of the Venturi meter, just described, the difference in level which will be obtained in the legs of the gauge is a measure of the fluid or gas flowing in the pipe to which the tube or nozzle is connected. The scale of the gauge can be graduated as desired, and though these simple instruments do not give any actual figures, they at least give indications which are comparative and will help to show the tendency of the plant, and whether an improvement in efficiency is being effected or otherwise.

The Measurement of Temperatures. Too often it is assumed when instruments are installed in a boiler-room that a knowledge of the coal consumption and the evaporation are all that is necessary for efficient operation. Undoubtedly appliances for the determination of these quantities will help considerably in this direction, but the figures obtained are only good over a period, and give no indication as to the state of the plant at any given instant. For this purpose it is necessary to know the temperatures existing in the various circuits; these are the furnace and gas circuit and the steam and water circuits. If measurements are made of the temperatures existing in

these circuits, the approximate efficiency of the boiler plant can be judged at any instant. If each boiler unit is equipped with means of ascertaining the temperatures at the various points of importance, not only can the approximate efficiency be judged, but the fireman or engineer-in-charge can readily tell the condition of the furnace and boiler, whether the fires are dirty, whether they have holes in them, whether the boiler is dirty inside or outside, and whether the brickwork and baffling is breaking down. The temperatures for various outputs obtained under good conditions, after cleaning the boiler, can be used as a standard from which to judge the performance of the unit. Invariably, manufacturers include thermometer pockets as part of the various units which go to make up the boiler plant, but very seldom does one find advantage taken of these fittings, and in many plants thermometers and pyrometers are looked upon merely as unnecessary ornamentation.

Thermometers and Pyrometers. For the lower ranges of temperature the ordinary mercury-filled thermometer is sufficient, but for the high steam temperatures now carried, nitrogen-filled mercury-in-glass thermometers should be used. All thermometers used in daily operating practice should be enclosed in some form of protecting shield otherwise, owing to their fragile construction, they will be easily broken. Care should also be taken when distributing thermometers throughout the plant that they are all graduated on the same scale, i.e. all Fahrenheit or all Centigrade. If both types are used, confusion is bound to result. Occasions may arise, of course, when, due to a shortage of the type of thermometer installed, use has to be made of one of another type. Conversion of the values is, however, an easy matter. If F. and C. represent Fahrenheit and Centigrade scales respectively, then—

$$\text{Fahrenheit} = \frac{9\text{C}}{5} + 32$$

$$\text{Centigrade} = \frac{5}{9} (\text{F} - 32)$$

The error in the ordinary thermometer may, where accuracy is desired, appreciably affect the results, and on boiler tests or when figures are desired to a close degree of accuracy, National Physical Laboratory instruments should be used. In the measurement of the higher ranges of temperature by

means of thermometers the stem error will, under test conditions, have to be taken into consideration. To obviate this stem error or keep it to a negligible value, "Selvey" type thermometers should be used for the measurement of steam temperatures. For ordinary operating practice the usual type of high temperature thermometer will give very good results if provision is made for inserting the thermometer in the pocket to within 20 or 30 degrees from the level of the mercury. Where high temperature measurements have to be made, the pockets should be at least 8 ins. deep and filled with mercury to the mark usually provided on high temperature thermometers. For the lower ranges of temperature oil is sufficient for the thermometer pockets. Good results will certainly follow the installation of mercurial thermometers, provided the boiler-room crew exert themselves sufficiently to read them. Often, of necessity, the thermometers have to be placed in rather out of the way positions and the result is that for a short period the instrument is diligently read, but once the first flush of enthusiasm is over it is neglected, and if readings have to be logged these are usually faked.

Location of Instruments. As already stated in an earlier part of the book, boiler-room instruments should, where at all possible, be mounted on one board in the firing aisle, and the electrical type of pyrometer is readily adaptable to this purpose. These instruments consist of two parts, a thermocouple and millivolt meter. The action of the instrument depends upon the potential difference set up when two conductors, each of a different metal, are joined at the end and exposed to heat. The potential difference is registered on a millivolt meter, the scale being calibrated to read in degrees F. or C. The thermocouple is fitted in the path of the fluid or gas, the temperature of which is being measured; leads are carried to the millivolt meter or recorder which can be installed in the most suitable position in the boiler-room. Instruments of this type are of great value in the measurement of steam and flue-gas temperatures, as they can be installed in a position readily observable.

Fig. 23 shows a group of these instruments on a large water-tube boiler unit. Another type of electrical pyrometer suitable for the same work as the instruments just described, operates on a resistance bridge principle. They are not quite so convenient as the former type of instrument, owing to the necessity of using an accumulator. They are, however, often

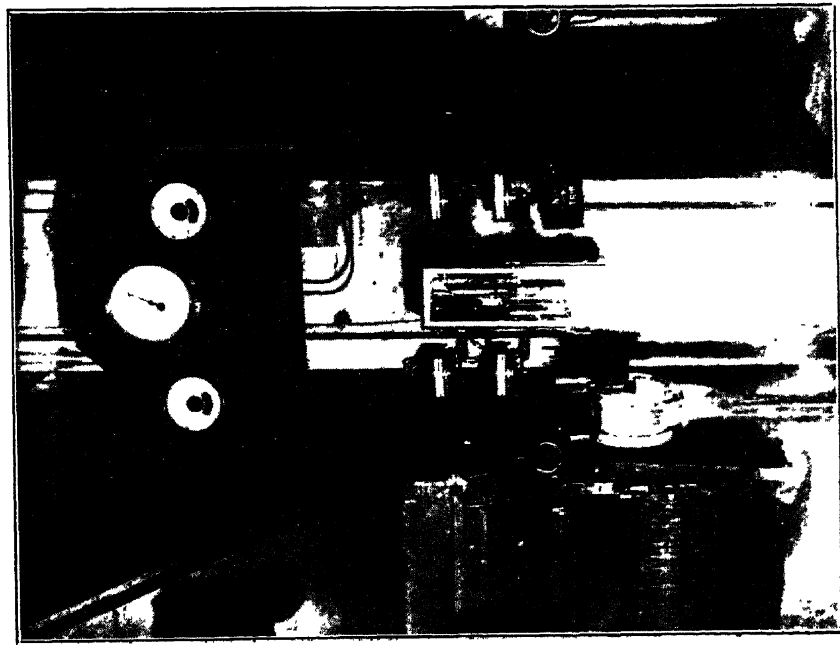


FIG. 23.—BOILER INSTRUMENT PANEL.

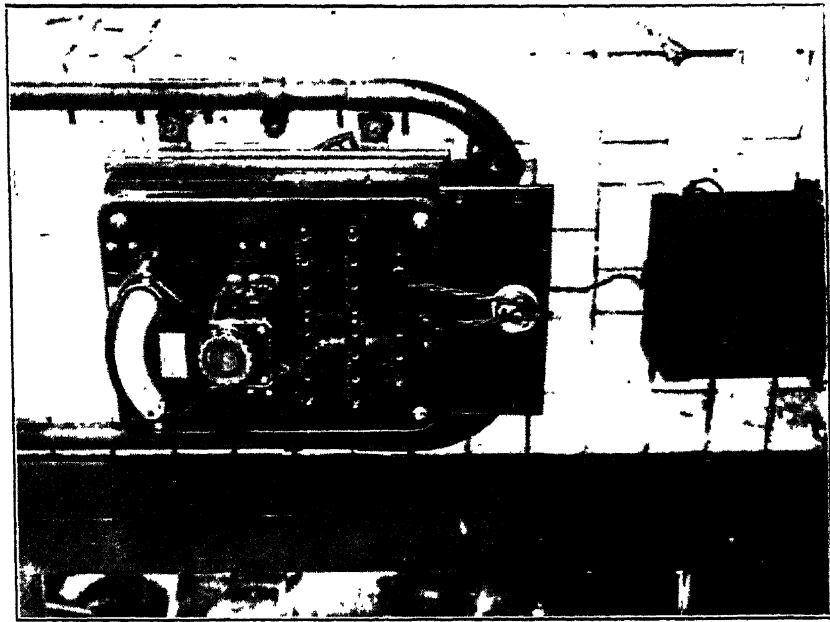


FIG. 24.—THERMOCOUPLE PLUG BOARD
AND INDICATOR.

installed where a wide range of temperatures has to be measured, one recorder or indicator being installed, provided with a multiway switch or plug board, the connections of which are taken to thermocouples at the various points where the temperature is to be measured.

Fig. 24 shows an instrument of this type installed for the measurement of hot-well water, economizer inlet and outlet water, and economizer inlet and outlet gas temperatures. Electrical pyrometers will not stand rough usage, and their upkeep and repair should be left entirely in the hands of one skilled man. They are delicate and expensive instruments and if properly looked after will give splendid service, for this reason they should be looked upon with respect by everyone in the boiler-room. Both types of instruments can be used either as an indicator or as a recorder.

Precautions Necessary. Modern installations of steam generating units are of such capacities that the areas of the boiler, economizer, and flue passes are very large. The temperatures of flue-gases are of no value in calculating a heat balance unless they are representative of all the gas handled. As thermometers only measure the temperature of the gas immediately surrounding the bulb, it can readily be seen that the result is not necessarily representative of the average temperature of the gas passing. The same can be said of thermocouples. Care must therefore be exercised when deciding the points at which temperature measurements of flue-gases are to be made, and a study of the flow of the gases, their tendency to bank to one side, set up swirling, etc., will no doubt be beneficial in deciding the most suitable points. A method of ensuring the average flue-gas temperature being accurately obtained consists in the use of resistance coils strung at intervals across the flue. The variations in resistance will be proportional to the variations in temperature, and can be read on a milliammeter calibrated to a temperature scale. In making arrangements for measuring flue-gas temperatures care must be taken that the point, where the thermocouple or other apparatus enters the flue, is carefully sealed to prevent the infiltration of air. Too great care cannot be taken in this matter for the least leakage of air will affect the readings.

Another point often overlooked in the installation of thermocouples is the effect on the thermocouple due to what are commonly termed radiation effects. If a thermocouple is inserted in the path of gases surrounded by bodies at different

temperatures, such as at points in the neighbourhood of economizers, errors in the indications of the gas temperature measured by the thermocouple will occur unless precautions are taken to minimize the effect of radiation.

Improperly installed thermocouples will give results with an error of 5.0 to 25.0 per cent in the temperature readings, the magnitude of the error depending upon the length of the exposed thermocouple, the velocity of the gases, and the temperature difference between the gases and the brickwork or heating surfaces.

Flue-gas temperatures in the neighbourhood of economizers can also be approximately determined by inserting a thermometer in a sand-bath, made from a large tin, and hung in the path of the gases. A suitable opening can be made through which the bath containing the thermometer can be lowered. An iron plate with an air-tight joint will serve as a lid, and the bath can be suspended from a hook screwed into the under side of the lid. This method is applicable in those stations where no pyrometers are installed for flue-gas temperature measurements. Precautions must be taken to ensure that the lid of the aperture makes a snug fit with the brickwork of the flue, otherwise the infiltration of air will rob the results of any value. Another type of temperature indicator consists of a small cylinder containing a liquid: this cylinder is inserted in the path of the gas or fluid and connected to a pressure gauge type of instrument by means of a small bore tube. Increase in temperature expands the liquid which, in turn, operates the mechanism of the gauge.

Measuring Furnace Temperatures. Furnace temperatures are very difficult to determine accurately. The electrical pyrometers, which have just been described, are quite satisfactory up to temperatures in the neighbourhood of 1,500° F., but beyond that point the thermocouple gives trouble. In ordinary operating practice it may not be necessary to know the furnace temperatures accurately, but when furnace conditions are being investigated some means must be employed to determine these values. This is best done by the use of a radiation pyrometer. These are usually of the disappearing filament type. The principle upon which instruments of this type operate can be seen from Fig. 25, and is based on the fact that the intensity of light from an incandescent body varies in a definite manner with the temperature. With the type of pyrometer represented in the diagram, the incandescent

furnace is compared with the brilliancy of the lamp filament, the resistance being varied until the latter disappears. The deflection on the galvanometer is then a measure of the temperature.

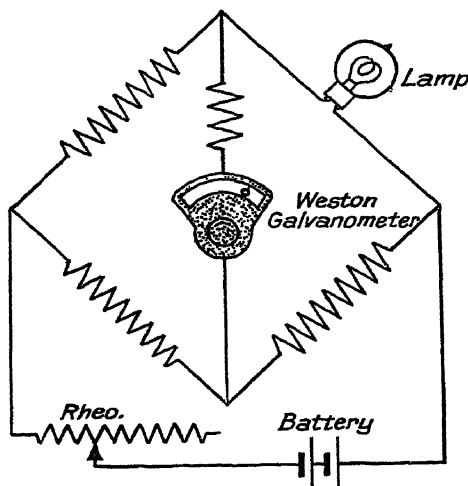


FIG. 25.—DIAGRAM "DISAPPEARING FILAMENT" PYROMETER.

filament and the image of the incandescent body are viewed through an eye-piece provided with a red glass to overcome any dazzling effect. The rheostat is then adjusted until the

One type of optical pyrometer is shown in Fig. 26. The diagram is practically self-explanatory. L is a lens through which radiation from the incandescent body, whose temperature is being measured, is brought to a focus at the point F . A metallic filament lamp is placed at F , and receives current from a small battery contained in a portable case, together with a rheostat and an accurate milliammeter. The lamp

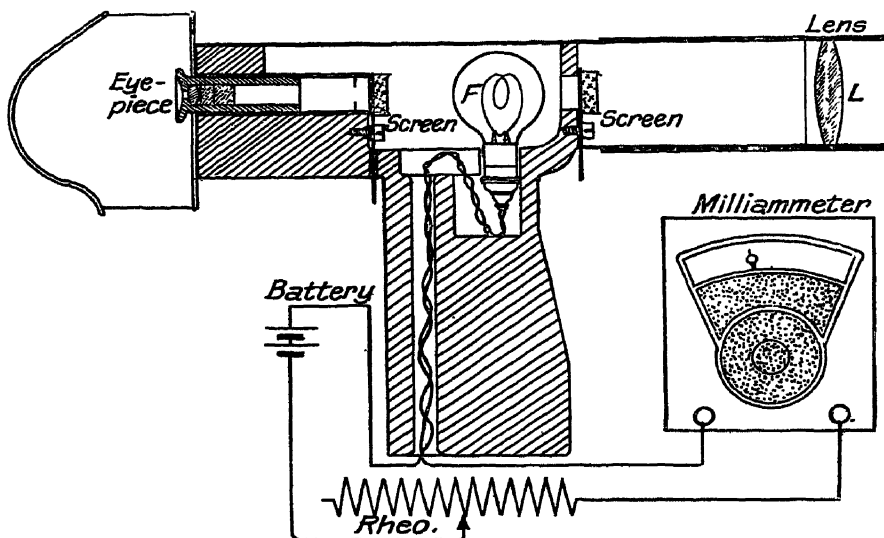


FIG. 26.—OPTICAL FURNACE PYROMETER.

filament seems to disappear, or becomes undistinguishable against the hot object, and the temperature is then read from the milliammeter direct, or from a curve with milliammeter readings as abscissæ and temperatures as ordinates. The curve is usually supplied with the instrument.

The colour, brilliancy, and appearance of the fire-bed and luminous gases are also a guide to the temperature of the furnace, and experienced, intelligent firemen can often judge the temperatures very accurately from these indications. The following table gives the approximate temperatures corresponding to the different appearances of the furnace. The indications given must be viewed in the dark—

Faint red to blood red	.	.	.	900° F. to 1,050° F.
Dull red to cherry red	.	.	.	1,050° F. to 1,500° F.
Bright cherry red	.	.	.	1,500° F. to 1,600° F.
Orange	.	.	.	1,600° F. to 1,700° F.
Light orange to yellow	.	.	.	1,700° F. to 1,950° F.
White heat to dazzling white	.	.	.	1,950° F. to 2,700° F.

High temperatures can also be approximately estimated from a knowledge of the melting points of various metals or salts. In the case of metals, these are made into cones and exposed to the heat of the furnace or gases. If salts are used, these are placed in small cast-iron boxes and treated in a similar manner. The following gives the various metals and salts suitable for this purpose—

Tin	.	.	.	450° F.	Sodium bromide	.	1,380° F.
Bismuth	.	.	.	520° F.	Potassium chloride	.	1,435° F.
Cadmium	.	.	.	575° F.	Sodium carbonate	.	1,570° F.
Lead	.	.	.	620° F.	Calcium fluoride	.	1,655° F.
Zinc	.	.	.	785° F.	Barium chloride	.	1,740° F.
Antimony	.	.	.	1,165° F.	Copper	.	1,980° F.
Aluminium	.	.	.	1,215° F.			

Air and Flue-gas Measurements. Reference has already been made to the necessity of measuring the temperature of the flue-gases, but for efficient operation it is also necessary to know their composition and the intensity of the draught drawing them through the boiler passes and flues. Draught measurements are easily made, and as the instruments for this purpose are by no means expensive to either buy or make, there is no reason for a boiler plant not being fully equipped with at least these necessary appliances. Draught gauges may be divided into two classes, the simple draught gauge

which indicates the difference in pressure between the outside air and the point to which it is connected, and the differential draught gauge which indicates the difference in pressure between any two points in the gas path to which the legs of the gauge are connected. Most engineers are fully familiar with the ordinary draught gauge, which consists of a glass U-tube, one end of which is open to the atmosphere and the other connected to the gas path. The gauge liquid is usually water or oil to which a dye has been added to give the reading

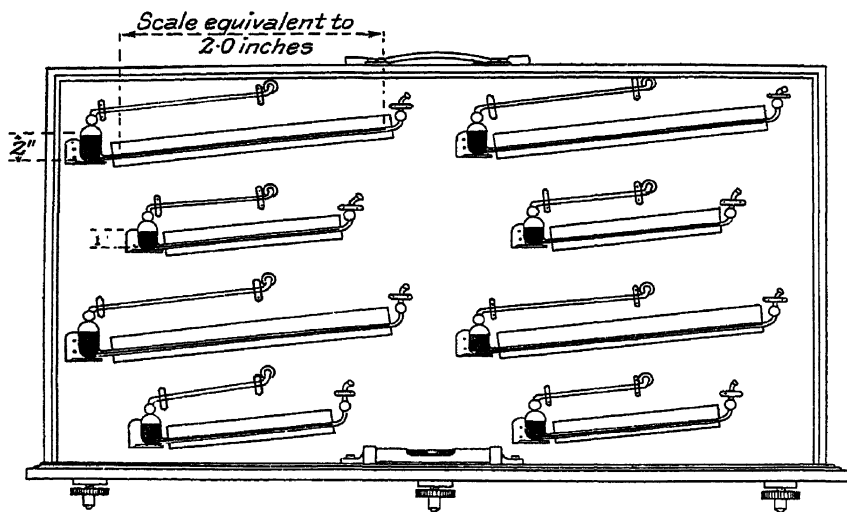


FIG. 27.—TEST GAUGES IN WOOD CASE.

prominence. Draught values are usually referred to in inches of water, and if oil is used care must be taken that the scale is properly calibrated, and when refilling the gauge the specific gravity of the oil must be the same as the oil being replaced.

A type of draught gauge now very widely adopted consists of a modified form of U-tube, one leg of which is inclined. Greater accuracy in reading the pressure is thus obtained. For test purposes and accurate investigations, where small differences in pressure have to be measured, this type of gauge is necessary. Fig. 27 shows a set of test gauges used for boiler-room work.

Any ordinary U-tube can be used as a differential gauge but, because of the greater accuracy obtained, the inclined leg type is to be preferred.

To Find the Weight of Flue-Gases. For efficient combustion each pound of coal being burned requires a definite amount of air, and with efficient operation the boiler output will be approximately proportional to the quantity of flue-gases. A differential gauge connected from the furnace to the uptake will therefore act as a flow meter and its indications will be proportional to the quantity of gases passing through the boiler. From the information so obtained, the proper quantity of air for a given set of conditions can be determined. The operation of most air meters, combustion meters (as distinct from CO₂ recorders), and efficiency meters is based on this principle. A satisfactory instrument of this type can be easily made by any engineer. If a Pitot tube is used in conjunction with the gauge it can be constructed on the lines previously described, only it must be long enough to reach across the entire length of the gas passes. This tube can be placed in the boiler uptake or flue. The connections from the tube are brought to the legs of the gauge, which can be fixed in any convenient position, preferably in the firing aisle. The weight of flue-gas is calculated as follows—

Let V = velocity of gases in feet per second

then $V = \sqrt{2gH}$

where H = hr.

h = reading on manometer or gauge

r = equivalent height of feet of gas

Let Q = cubic feet per hour

then $Q = 3,600 V.A.$

where A = area of flue in square feet

Let W = weight in lbs. of flue-gas

then $W = Q \times 0.0761$ (approx.)

This, however, is only true if the gases were at 60° F. The weight of the flue-gases corrected for temperature is found from the formula—

$$W \times \frac{522}{T}$$

where T = absolute temp of flue-gases in ° F.

An example will make the description of the use of the gauge more clear.

Assume the reading on the gauge to be 0.12 ins. of water
 $= h$, $r = 68$ —

$$\begin{aligned}\text{Then } V &= \sqrt{2gH} \\ &= 22.9 \text{ ft. per second}\end{aligned}$$

$$\text{Temp. of flue-gases} = 400^\circ \text{ F.}$$

$$\text{Area of flue} = 45 \text{ sq. ft.}$$

$$\therefore W = 288,000 \text{ lbs. per hour at } 60^\circ \text{ F.}$$

$$\text{and at } 400^\circ \text{ F.} = 288,000 \times \frac{522}{862}$$

$$= 174,500 \text{ lbs. flue-gas per hour.}$$

Innumerable uses can be found for instruments of this type in the boiler-room, but if used for flue-gas measurement or air regulation, care must be taken of the boiler setting, otherwise, due to air leakage, erroneous results will be obtained.

If the gauge be used for indicating combustion conditions, one leg of the gauge is connected to a point over the fire-bed and the other leg to the boiler uptake. Tests are then run on the boiler to ascertain the best conditions of air supply for various outputs, etc., and these points are marked off on the gauge scale. Further, a differential gauge connected to show the pressure-drop across the fire-bed, used in conjunction with one showing the drop across the boiler, will indicate any change in firing conditions. The two connections for a differential gauge should, if possible, be placed on the same level, otherwise a correction will have to be applied for the difference in weight of the columns of gas in the pipe connections. This correction is negligible in ordinary working.

Anemometers have been suggested by various authorities for measuring furnace air supply, but good results are not obtained unless the measurement is made where the flow is approximately equal throughout the cross-section of the air passage. To ensure this, it may in some cases be necessary to construct a wooden duct leading, either to the forced draught fans or grate fronts.

The control of furnace air supply is effected by varying the fan speed or the position of the damper. The ash-pit doors must never be used for draught regulation. Doing so, robs the fire-bed of the air supply, heats up the fire-bars or grate links, and warped grates are the result. Closing the ash-pit doors also increases the infiltration of air through leaky settings. The range of damper control should be calibrated for each

boiler by connecting a differential gauge across the damper. The damper is then placed in the fully closed position and gradually opened until the first movement of the gauge is noticed, this point is marked on the damper control gear. The opening of the damper is then continued until no further pressure drop is registered. This point is also marked on the control gear. In daily operation dampers must never be quickly operated, but changing from one position to another must be done gradually. In the smaller stations it is customary to regulate the draught for all the boilers by means of one damper in the main flue, and where this method is in use care must be taken that the draught is equally distributed on all boilers, otherwise it will be impossible to maintain good furnace conditions. Damper controls must be mounted on the front of the boiler in the firing aisle, and in large modern power stations draught fans should also be controlled from this position. Automatic dampers which vary with the steam pressure are in use in some places, but they have not been adopted to any great extent in power stations in this country.

Volumetric Analysis of the Gases of Combustion. The analysis of the gases forming the products of combustion provides a means for keeping at a minimum the major heat losses in boiler-room operation. From such an analysis and a knowledge of the temperature of the gases leaving the last of the heating surface of the boiler unit, a good idea of the efficiency of the plant can be obtained. From a knowledge of the composition of the coal, and the composition and temperature of the escaping gases, the various losses can be separated and estimated, and methods established for their reduction. The processes of measuring and analysing gases involve the use of comparatively cheap and simple apparatus, and the readings are indicated in such a way as to be easily understood by the average fireman. We have seen in an earlier part of the book that if a combustible containing 100 per cent carbon in unit weight were perfectly consumed, the products of combustion would be 79.2 per cent by volume of N and 20.8 per cent by volume of CO_2 . However, as no coal contains 100 per cent combustible in the form of carbon, it is impossible, even if perfect combustion could be obtained in the best of modern furnaces, to obtain 20.8 per cent as the CO_2 content of the flue-gases. A method of calculating the CO_2 obtainable from a coal of known composition has been given.

Gas Sampling. When using apparatus for analysing flue-gases, great care must be taken that the sample of gas is representative of that to be analysed. A long lance with holes at intervals along its length is suitable for use with the portable Orsat apparatus, but a better method, when gas analyses have to be made at various points, is to make a permanent fitting of a five or six-legged spider made of tubing suitably perforated. By this means a good average sample of the gas flowing in every part of the cross-sectional area of the flue is obtained. For permanent combustion indicators or recorders the most suitable points from which the sample should be drawn are the uptake or the last pass of the boiler. For test purposes, and when taking samples for laboratory analysis, aspirator bottles are useful, but if a large sample of gas is required a specially constructed receiver, similar to a small gasometer, should be installed. We have seen that if a coal of a given composition is completely consumed a definite percentage of CO_2 is formed, therefore in boiler-room work if an instrument to measure CO_2 is inserted in the path of the escaping flue-gases, its indications will be a measure of the completeness of combustion. Most CO_2 recorders and indicators for commercial application measure the percentage of CO_2 in the flue-gases by the absorption of the CO_2 in a suitable reagent.

The Orsat-Lunge apparatus, Sarco, WR combustion recorder, and the Simmance-Abady CO_2 combustion recorder, are typical instruments using a CO_2 absorbent. The gas sample is usually drawn to the instrument by means of a small air or steam-jet aspirator, or if induced draught is employed the instrument may be connected across two points in the gas path, for instance, from the uptake to the eye of the fan, the difference in pressure being sufficient to draw a continuous stream of gas through the instrument.

The WR Combustion Recorder. The WR instrument can be obtained either singly as an indicator or as a combined indicator and recorder. It is extremely simple to understand and requires the minimum of attention, but care must be taken to keep the instrument and gas pipes free from deposit and in a tight condition, as the smallest air leak in the gas circuit will upset its operation. Copper tubing should not be used to connect the instrument to the flue. Tubing of this material becomes clogged in a very short time with a copper sulphate deposit, necessitating frequent blowing through with steam or compressed air. The author finds that tubing of

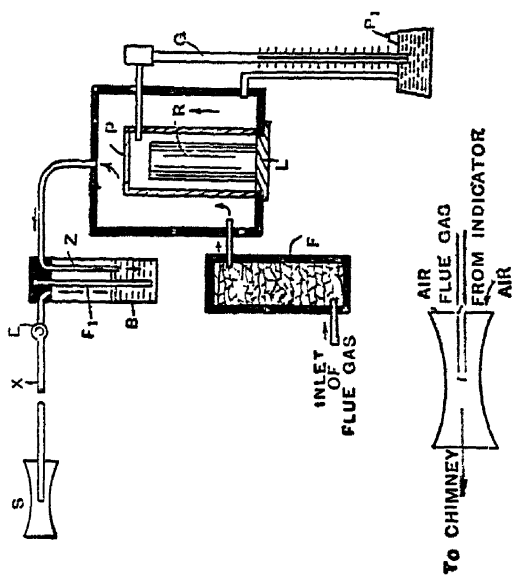
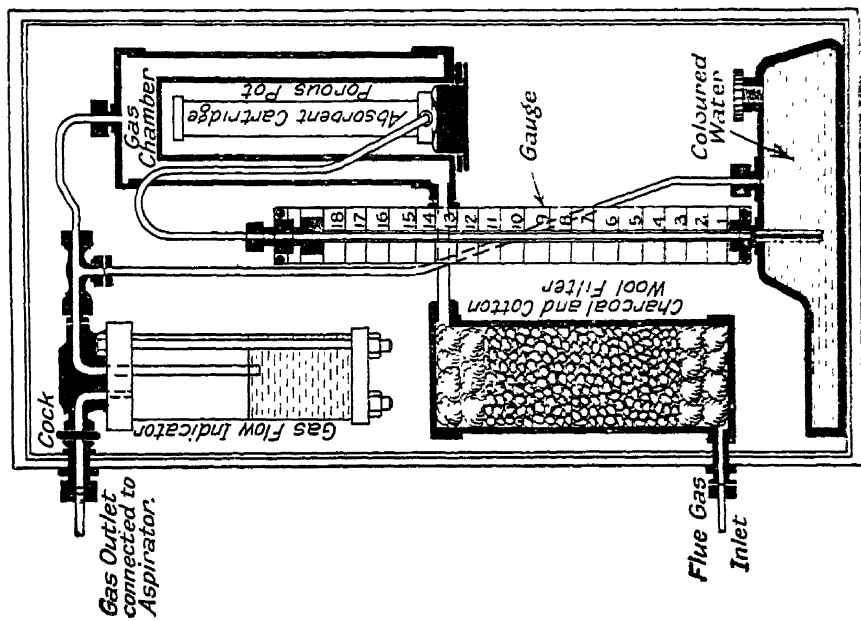


FIG 28.—VIEW SHOWING GAS TRAIN

ordinary lead composition is very suitable for making connections. The principle of operation of the instrument can be clearly followed from Fig. 28. In all the CO_2 measuring instruments, either recording or non-recording, which are now on the market it is highly important to keep the vital parts of the apparatus in an efficient condition in order to obtain reliable results. In large power stations each boiler should be equipped with its own CO_2 indicator or recorder, but in the smaller plants one or two such instruments are sufficient, provided a piping system is installed so that an instrument can be connected to any one boiler. Simply connecting the instrument to the main flue is not sufficient, as no means are then available for determining a faulty boiler unit when a low CO_2 is indicated.

Indicators and recorders which depend upon the absorption of the CO_2 for their action have, of necessity, owing to their construction, to be placed at some distance from the point at which the gas is being sampled, and the length of tubing required introduces a time lag which in some instances may be quite serious.

The Cambridge CO_2 Recorder. A type of instrument which almost eliminates this time lag has been developed by the Cambridge Scientific Instrument Co. The instrument is an entirely new departure from the older methods of boiler-room gas analysis, and its action is based on the difference of conductivity of air and flue-gas containing varying percentages of CO_2 . Fig. 29 is a diagrammatic arrangement of this type of instrument. Two identical spirals of platinum wire are enclosed in two separate cells, E^1 , E^2 , in a metal block. Each of these spirals forms one leg of a Wheatstone bridge circuit. Current is allowed to flow through the bridge, thus heating the spirals which lose heat to the walls of the cells. The current in the bridge circuit is adjusted to a constant amount by the rheostat R . If the two cells contain gases of different thermal conductivities the spirals will cool at different rates, and one spiral will therefore be maintained at a higher temperature than the other. The difference in temperature of the two wires causes a deflection of the galvanometer G , the extent of which depends on the difference of conductivity of the two gases. The construction is such that changes in the temperature of the gases affect both sides of the bridge equally. If, therefore, the cell E^1 contains a pure gas and the other cell E^2 the same gas mixed with some other constituent, the extent

of the deflection will be an indication of the amount of the second gas present, and the galvanometer can be calibrated to show directly the percentage composition of the mixture. In practice, one cell is filled with air saturated with moisture and the other is exposed to the gas under test. The difference in conductivity of the gases in the two cells then depends solely on the percentage of carbon dioxide in the gas. The metal block containing the cells can be fixed close to the point where the gases are to be sampled, and as the connection to the indicating or recording instrument is purely electrical, the time

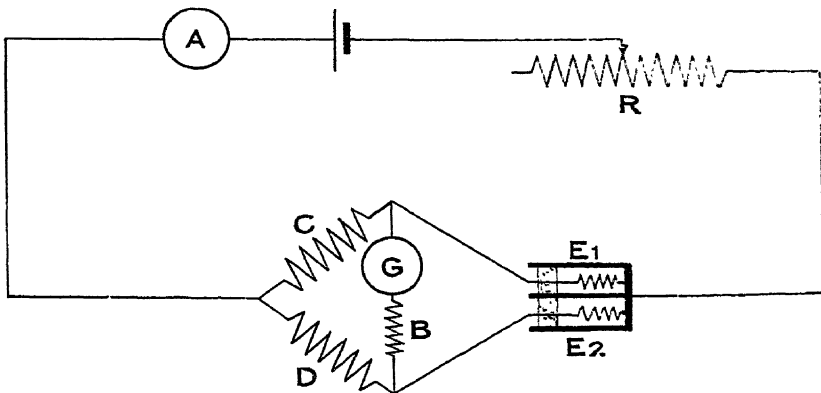


FIG. 29.—CAMBRIDGE CO₂ INDICATOR ;
DIAGRAM OF CONNECTIONS.

lag is very short, and the apparatus can be placed in any convenient position for easy observation. As the instrument is quick in action it is only necessary to install one indicator or recorder, and a multiway switch to connect the instruments to the cell blocks fitted on the various boilers. The percentage of CO₂ in the flue-gases is by itself only a measure of the efficiency of combustion, and gives no indication of either the heat carried away by the flue-gases, or the approximate efficiency of the boiler. To know these values a knowledge of the temperature of the escaping flue-gases is necessary, and a good point about the Cambridge CO₂ instrument is that the temperature of the gases can be indicated or recorded along with their corresponding CO₂ content. It must be understood, of course, that while a CO₂ indicator or recorder is, generally speaking, a reliable guide to furnace efficiency, there are certain factors which must be considered in conjunction with the indications of the instrument.

Depending upon the quality of the coal and the efficiency of the air-mixing arrangements, there is a critical point beyond which an increase in the percentage of CO_2 results in a loss. This point represents the minimum excess air with which the furnace can be operated; any further reduction in air quantity results in the production of CO and unburnt hydro-carbon gases. In practice, this critical point of combustion can only be found by experiment; but, generally speaking, it will be in the neighbourhood of 14.00 per cent CO_2 .

An instrument which indicates the critical point of combustion is the Mono-duplex Recorder. The gas sample is drawn to the instrument by means of a form of water-operated mercury pump; it is then measured to 100 c.c. in a "volumeter" integral with the instrument and discharged through a directing valve to the K.O.H. absorption solution, the residual gas being discharged to a form of small gasometer which operates the recording mechanism. This operation records the percentage of CO_2 in the sample. The next sample of gas is, by means of the directing valve, passed through a small electric furnace before being discharged to the absorption solution. Doing so ensures that any combustible gases in the sample are completely consumed. Any carbon monoxide is burned to CO_2 , hydro-carbon gases to CO_2 and H_2O , and H_2 to H_2O . The chart record will now show a greater value than when only CO_2 was measured, the difference between the first and second record being the percentage of combustible gases present in the flue gases. A noteworthy feature of the instrument is the care with which the gases are treated before reaching the analysing apparatus. These are so carefully filtered and dried that only $\frac{1}{8}$ -in. diameter pipe is used to convey the gas sample to the instrument, thus appreciably shortening the time lag.

For test purposes and special investigations of boiler and furnace conditions, a more elaborate system of gas analysis has to be adopted, involving the use of delicate apparatus requiring skilled operation. Questions relating to furnace conditions, such as air supply, firing, air leakage, short circuiting of gases, etc., involve the estimation of carbon dioxide, oxygen, carbon monoxide, and nitrogen. This is usually done by a special apparatus, such as the Orsat-Lunge, in which the gases are absorbed *in the following order* by the reagents specified—

(a) CO_2 (Carbon dioxide) by potassium hydrate solution.

BOILER-ROOM MEASUREMENTS

- (b) O₂ (Oxygen) by alkaline pyrogallate solution.
- (c) CO (Carbon monoxide) by freshly prepared cuprous chloride in acid solution.
- (d) N (Nitrogen and H_nC_m) by difference, i.e.—

$$100\% - (\text{CO}_2\% + \text{O}_2\% + \text{CO}\%).$$

For very accurate work and where exhaustive investigations have to be made, it is necessary to determine the carbon dioxide, oxygen, carbon monoxide, hydrogen, methane, nitrogen, etc. This involves the use of a special laboratory to which a large representative sample of the gas can be taken in suitable containers. In this case the process of analysis is usually carried out by means of Hempel burettes. For the usual gas analysis in connection with power station boiler-room testing, the Orsat apparatus, previously mentioned, cannot be bettered. It gives accurate results, is easily transported, requires practically no assembling, and in the hands of an experienced operator analyses at different points can be fairly quickly carried out.

Fig. 30a is an Orsat-Lunge apparatus.

The complete equipment, with the exception of the sampling gear, is mounted in a wooden case. The essential parts of the apparatus are a levelling bottle *A*, measuring burette *B*, graduated in 100 divisions and water-jacketed to prevent changes of temperature affecting the gas volume, the absorption pipettes *P*¹, *P*², *P*³, and the connecting tube *T*. The pipettes are in the form of U-tubes with bulbous legs, Fig. 30b, one leg of each being connected to the main connecting pipe *T* and the other leg open to the atmosphere. Cotton-wool or a small cork should be kept in the openings of the latter when the instrument is not in use. In some instances these openings are connected to a flexible rubber bag into which the air is displaced by the reagent when an analysis is being made. The bulbous part of the legs connected to the tube *T* are filled with small glass tubes so that a large absorption surface is exposed to the gas when the reagent is displaced in the pipette. The reagents for the pipette are as follows—

(a) *P*¹ contains a solution of potassium hydrate for the absorption of CO₂. This solution can be prepared by dissolving 500 grams of the commercial hydrate in 1,000 c.c. of water; 1 c.c. of the solution will absorb 40 c.c. of CO₂.

(b) *P*² contains a solution of potassium pyrogallate for the absorption of O. This solution is prepared by dissolving

5 grams of the solid pyrogallic crystals in 100 c.c. of potassium hydrate; 1 c.c. of this solution absorbs 2 c.c. of O . As this solution readily absorbs oxygen from the atmosphere it should not be prepared until shortly before the gas apparatus is to be used.

(c) P^3 contains a solution of either acid cuprous chloride or ammoniacal cuprous chloride. The former is prepared from

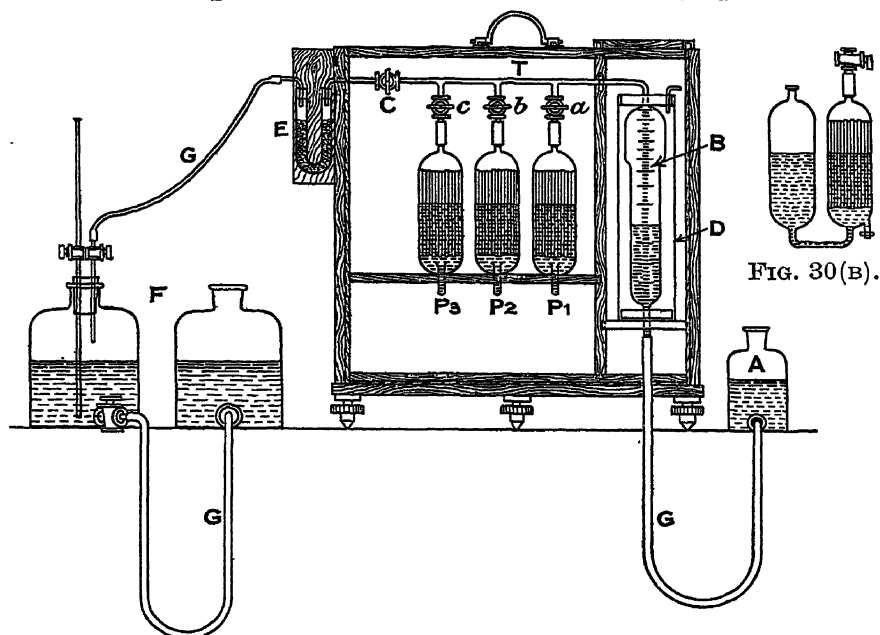


FIG. 30(A).—ORSAT FLUE GAS TESTING APPARATUS.

- | | |
|----------------------------------|--|
| A = Levelling bottle. | F = Aspirator bottles. |
| B = Graduated barette. | G = Main connecting tube. |
| C = Three-way cock. | a, b, c = Cocks for absorption pipettes. |
| D = Burette water jacket. | P_1, P_2, P_3 = Absorption pipettes. |
| E = U-tube cotton wool filter. | G = Flexible rubber tubing. |

copper oxide, copper wire, and hydrochloric acid. The bottom of a bottle used for a stock supply is covered with a layer of copper oxide, pieces of copper wire are then made into a bundle and long enough to reach from top to bottom of the bottle. Hydrochloric acid sp. gr. 1.10 is then filled into the bottle, which is occasionally shaken and, when the solution is colourless, may be decanted into suitable bottles, the stock being made of as required with hydrochloric acid.

Authorities are at variance as to the absorption capacity of this solution, but the figure generally adopted is 1 c.c. of CO per c.c. of solution.

The pipettes are each about half-filled with their respective solutions and the bottle *A* is filled with coloured water to a height sufficient to ensure that when raised to its highest position the outlet tube will not be uncovered. When making an analysis the gas sample may be drawn either by a lance, as already referred to, aspirator bottles, or a small steam, water, or compressed air aspirator jet. The analysis of the gas is carried out as follows. By means of the levelling bottle, the levels of the reagents in the pipettes are adjusted to a mark usually made on the neck of the front leg of each pipette. The liquids are kept at this level by closing the cocks *a*, *b*, *c*, as each reagent is adjusted. The header-tube *T* is connected to the sampling gear leading to the gas pass or sample bottle, and the three-way cock *c* is opened to connect *T* with the atmosphere but not with the flue-gas. The levelling bottle is then raised, thus flooding *B* and expelling the air from the instrument. Care must be taken when using the levelling bottle that the water is not forced into *T* and the pipette connections, a pinch cock on the rubber tubing of the levelling bottle will help to prevent this. Cock *c* is turned so as to shut off the atmosphere and open the apparatus on to the gas. The bottle *A* is then lowered and a charge of gas drawn into the burette. This should be repeated half-a-dozen times to clear the tube passages of any air and to saturate the water with the gases being measured. When the sample is drawn, which is to be analysed, the bottle *A* is carefully raised or lowered until the meniscus of the water in the burette registers with the bottom graduation, zero or 100, as the case may be. The cock *c* is again turned to shut off both gas and atmosphere from the apparatus. Cock *a* is then opened and the bottle *A* raised and lowered, thus forcing the gas sample into and out of *P*¹. This is repeated about half-a-dozen times, finally finishing the absorption of CO₂ in *P*¹ by adjusting the level of the reagent to the mark on the neck of the pipette. The bottle *A* is then adjusted until the level of the liquid in it coincides with the level of that in the burette. If the zero graduation is at the bottom of the burette the reading at the meniscus of the water in the burette is the percentage of CO₂ by volume in the gas.

The same procedure is gone through with *P*², and the reading on the burette at the end of the absorption is the percentage of CO₂ plus the percentage of oxygen. The CO is determined in a similar manner by absorption in *P*³. When

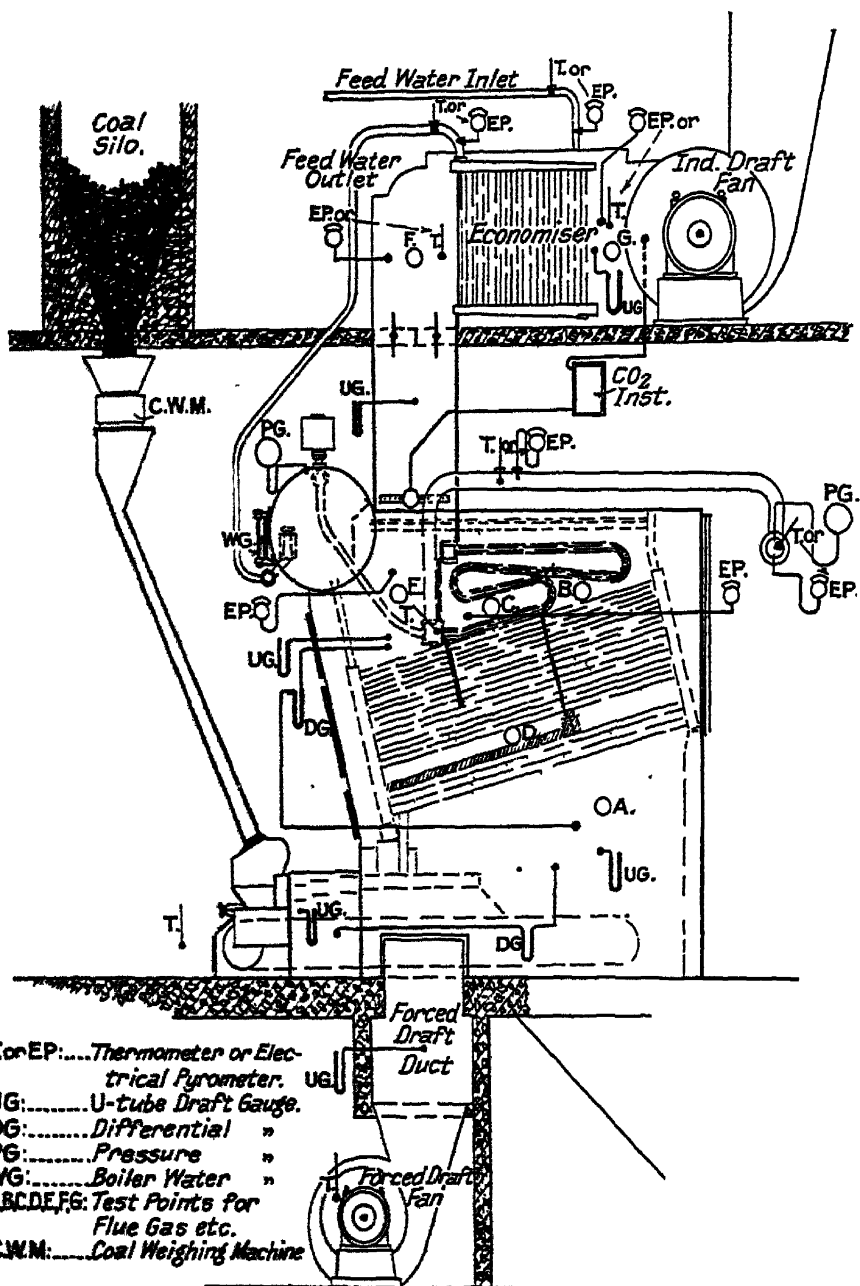


FIG. 31.—TEST POINTS ON BOILER UNIT.

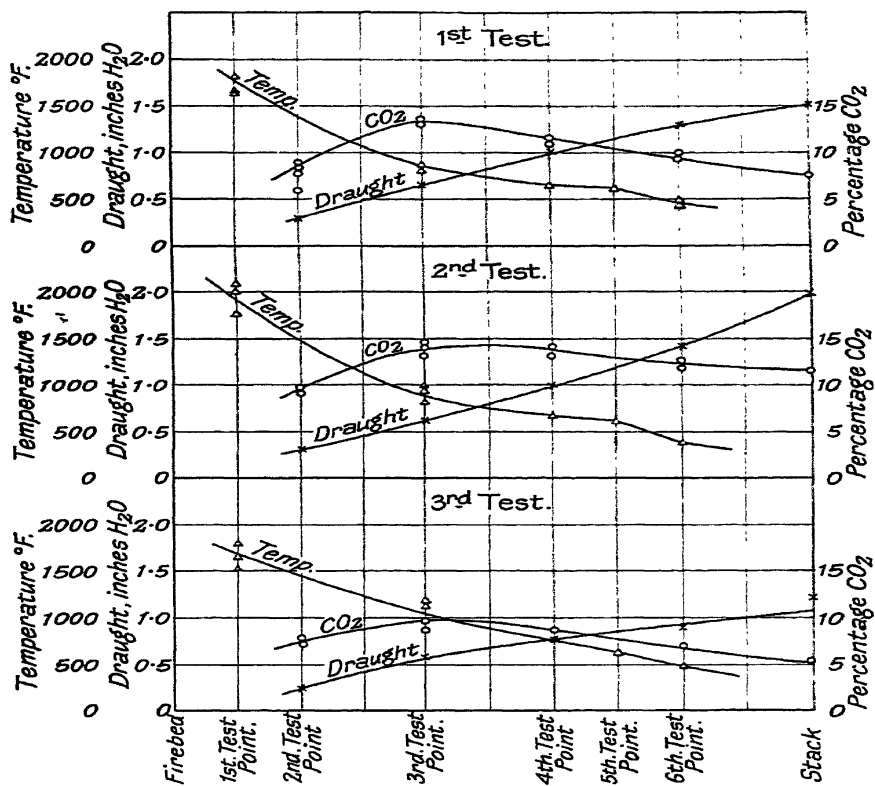


FIG. 32.—BOILER TEST CURVES OF CO₂. TEMPERATURE, AND DRAUGHT VALUES.
Wade's Diagram.

making a gas analysis CO_2 is always the first gas to be removed, and it is important when using the Orsat apparatus that the gas be admitted to the reagents in the order given, and a sufficient number of passes in and out of the pipette made to ensure complete absorption, before passing the residue on to the next reagent. After each analysis the number of cubic centimetres found of CO_2 , O, and CO, should be entered on a card and kept totalled. By subtracting the total from the absorption capacity of the reagents, their condition is known at any time, and they can thus be renewed before causing errors in analysis.

The points to which the various boiler-room instruments should be connected depend upon the type of boiler installed and the general layout of the boiler-room plant. Fig. 31 shows diagrammatically the arrangement of test points on a water-tube boiler unit. It is not necessary, of course, that instruments be coupled to all the points indicated in the diagram. Arrangements to suit a particular plant will no doubt suggest themselves from the figure. An efficient method of investigating and checking boiler performance is that described by C. F. Wade, in *Efficient Boiler Management*. Briefly, it consists in drawing up a set of curves showing the relations between draught, temperature, and CO_2 from observations made at various test points. Once the best combination of conditions has been found and curves plotted of the values, any falling off in efficient performance is easily noticed. An example of sets of curves is shown in Fig. 32.

•

CHAPTER V

RECORDING, TABULATING, AND ANALYSING OPERATING RESULTS

POWER stations which do have a system of recording and tabulating the operating results are too addicted to the practice of making one log sheet serve the whole station. This sheet usually contains the most minute information concerning generator and feeder loads, but seldom, alas, are any figures to be found concerning the steam side of the station. It is imperative, if the best results are to be obtained, that a separate log sheet be provided for the boiler and turbine rooms. The purpose of instruments in the boiler-room has already been discussed, but if an analysis is to be made of the boiler-room operating results, the indications from the various instruments must be carefully logged at least every half-hour. From the information so obtained a heat balance can be drawn up. The usual method of stating the distribution of the heat units is in the form of a balance sheet, showing the various efficiencies and the apportioning of the losses. An example of the data necessary for test purposes, from which the boiler plant performance can be thoroughly judged and from which a heat balance statement can be accurately computed, is set out in detail below (Table X). In daily operation it is impossible to make such lengthy deductions, and only the principal factors for the analysis of the daily operating results need be considered.

TABLE X
REPORT ON BOILER TRIALS

Boiler Nos.	
Tests carried out by	
Class of Boilers	
„ of Economizers	
„ of Stokers	
Total Grate Area	
Boiler Heating Surface	
Superheater Heating Surface	
Economizer Heating Surface	
Class of Fuel used	
Average Price per Ton	
Date of Test	
Duration of Test	

COAL

Proximate Analysis. (Moisture Free and As Fired)

Total Moisture % Fixed Carbon.%

Volatile Matter % Absolute Ash%

Remarks on appearance and nature of Coke and Ash

Ultimate Analysis. (Moisture Free or As Fired.)

Moisture % Nitrogen%

Carbon % Sulphur%

Hydrogen % Absolute Ash%

Oxygen % Available Hydrogen%

Calorific Values, by Bomb-type Calorimeter.

B.T.U.'s per pound (Moisture Free)

B.T.U.'s per pound (As Fired)

Total Coal measured lbs.

Sample for Analysis lbs.

Total Riddlings lbs.

.. Coal in Riddlings. lbs.

Total Ashes removed from Ashpits lbs.

Carbon in Ashes removed from Ashpits lbs.

Actual Ash removed as Percentage of Coal consumed %

Total Actual Coal Consumed lbs.

(equals total coal metered minus sample for analysis plus coal in riddlings)

Average Coal Consumption per Hour lbs.

WATER

Total Water Evaporated (Test Tanks) lbs.

.. .. (Lea Recorder) lbs.

.. .. (Boiler-flow Meters) lbs.

Average Evaporation per Hour (Test Tanks) lbs.

.. .. (Lea Recorder) lbs.

.. .. (Boiler-flow Meters) lbs.

.. Temperature Boiler-room Hot-wells ° F.

.. .. Economizer Inlet ° F.

.. .. Outlet ° F.

.. .. Rise of Water ° F.

Actual Evaporation per Pound of Coal lbs.

STEAM

Average Boiler Pressure lbs./□" g.

.. Total Temperature ° F.

.. Degrees of Superheat ° F.

Factor of Evaporation.....

AIR AND GASES

Average Temperature (Dry Bulb) ° F.

.. .. (Wet Bulb) ° F.

Humidity %

AIR AND GASES (*contd.*)—

Average Temperature	Air entering Pre-heater	° F.
"	" Air leaving Pre-heater	° F.
"	" " entering Grates	° F.
"	" Gases at Uptake	° F.
"	" " at Economizer Inlet	° F.
"	" " at Economizer Outlet	° F.
"	" Drop of Gases	° F.

Gas Analysis by ORSAT—

Average	CO ₂ content per cent volume	
"	O ₂ " " "	
"	CO " " "	
"	N ₂ , etc., by difference	

DRAFT (measured in inches H₂O)

Average at	Forced Draft Duct	
"	at Right-wing Air Supply Box	
"	at Right-centre Air Supply Box	
"	at Left-centre Air Supply Box	
"	at Left-wing Air Supply Box	
"	at Right-grate Air Chambers	
"	at Centre-grate Air Chambers	
"	at Left-grate Air Chambers	
"	Over-fires (front)	
"	" (back)	
"	at Uptake	
"	at Stack	

AUXILIARIES

Total Kw.-Hrs.	Induced Draft Fan	
"	" Forced Draft Fan	
"	" Stoker Drive	
"	" Electrical Feed-pump	
	Total Kw.-Hrs.	

RESULTS

Coal Consumed per Square Foot of Grate per Hour.	lbs.
B.T.U.'s liberated per Square Foot of Grate per hour	
" transferred to Water and Steam per Pound of Coal	
" transferred per Square Foot of Boiler Heating Surface per Hour	
" transferred per Square Foot of Superheater Surface per Hour	
" transferred per Square Foot of Economizer Heating Surface per Hr.	
Actual Evaporation (lbs. water per lb. of coal)	lbs.
Equivalent Evaporation from and at 212° F.	lbs.
" " from and at 212° F. per 10,000 B.T.U.'s in coal.	lbs.
Cost of Evaporating 10,000 lbs. of Water from and at 212° F.	s. d.

OPERATION OF FIRES

Fire-bed Thickness. Grate Speeds, etc.—

Theoretical Air required per Pound of Coal as Fired lbs.

Actual Air per Pound of Coal as Fired lbs.

Average Excess Air per Cent

Remarks on Smoke Observation, etc.—

HEAT BALANCE PER POUND OF COAL.		B.T.U.'s	Per Cent 100-00.
To Calorific Value of Coal as fired—			
By Heat Transfer in Boiler			
.. .. Superheater			
.. .. Economizer			
By Heat Transfer in Combined Plant			
.. Loss in Dry Flue Gases			
.. .. in Moisture in Coal			
.. .. in Moisture from Combustion of Hydrogen			
.. .. Due to Incomplete Combustion of Carbon (CO)			
.. .. in Combustible in Ash			
.. .. in Radiation			
.. .. in Moisture in Air			
.. .. in Heat in Ashes and Losses Unaccounted for			

Report of Test, General Conclusions, etc.

The following, Table XI, are the daily log sheet readings which should be taken of the instruments on each boiler and entered in the boiler-room log sheets, scrap logs being provided for other information. It is usual to provide a separate log sheet for each day, the first reading being entered at midnight and the last reading entered the following midnight. When completed each column is averaged. This does not mean just totalling the figures in each column and dividing by the number of readings, and unless the averaging is done in a scientific manner the results obtained will be useless for heat balance computations. For instance, in averaging the flue gas temperatures for the various boilers, account must be taken of the gas volumes, which will vary with the load, quality of coal, and methods of firing. The correct method of averaging the flue gas temperatures,

TABLE XI
BOILER NO.

[illegible]

then, would be by taking into consideration the weight or volume of the gas. It is impossible to do this accurately under the conditions obtaining in most stations, but if a steady CO_2 is maintained the boiler output or the coal consumed will vary fairly approximately to the flue gas volume or weight, either of these values can then be substituted for the gas volumes. The average CO_2 is calculated by taking into consideration the amount of coal consumed.

The same care must be taken in averaging the steam pressures and temperatures, and feed-water temperature readings, to obtain true averages and accurate results. That done, we now have the necessary data from which to compute the boiler-room heat balance. It should be clearly stated whether the heat balance is based on "dry" coal values or coal "as fired." There is at present no definite rule as to what calorific value shall be used to calculate the various efficiency percentages and percentage losses, and it is therefore imperative to state in the heat balance whether the "higher" or "lower" calorific value has been used.

The "higher" calorific value, as already stated, is the value as determined by the calorimetric test, without any deductions, expressed in terms of B.T.U.'s per pound of dry coal or coal as fired.

The "lower" calorific value attempts to make allowances for the latent heat of the steam or water-vapour formed by the combustion of the hydrogen content of the coal, and the difference between the "higher" and "lower" value is therefore the total heat of the steam or water vapour in the flue gases, less the sensible heat of an equivalent weight of water at the temperature at which the coal and air were fed to the furnace. Much controversy exists as to the temperatures for use in calculating the "lower" heating value. The following are the necessary items to be calculated for the construction of a heat balance statement based on the "gross" or "higher" calorific value of the coal as fired, the latent heat carried away by the steam or water vapour formed by the combustion of hydrogen, being calculated as an item in the losses. Each item is calculated as a certain number of B.T.U.'s per pound of coal on the basis selected, and is entered on the balance sheet as such and also as a percentage—

(a) Heat absorbed by boiler, superheater, and economizer per pound of coal. The value can either be expressed in the aggregate, or the efficiency of each component may be

expressed separately. The latter method is the better and aids the localizing of losses.

(b) Heat lost in dry chimney gases per pound of coal.

(c) Heat lost in latent heat of steam or water vapour formed by the combustion of the hydrogen content per pound of coal.

(d) Heat lost due to incomplete combustion of carbon per pound of coal, i.e. carbon burning to CO instead of CO₂, or CO₂ being reduced to CO.

(e) Heat lost due to combustible, assumed to be carbon, carried over in the ash per pound of coal.

(f) Heat lost due to moisture content per pound of coal.

(g) Heat lost due to moisture in the air supplied per pound of coal.

(h) Heat lost due to radiation. Though commonly termed radiation losses, these are, strictly speaking, the losses due to convection and conduction from the furnace and boiler setting, etc.

(i) Errors in observation, unaccounted for losses, etc.

Under daily operating conditions it requires a high degree of boiler-room organization to obtain the necessary data from which the losses can be separately calculated and tabulated in the foregoing manner, but if efficient operation is to be maintained, the value of each loss must be readily ascertained and the sources of loss kept under continual surveillance.

The combined efficiency of boiler, superheater, and economizer can be calculated from the following equation—

$$\text{Thermal efficiency of combined plant} = \frac{E \times (H - h_1) \times 100}{C}$$

where E , is the actual evaporation per lb. of coal, as found by dividing the total water evaporated by the total coal consumed ; where H , is the total heat in the steam. This value can be read from standard steam tables or heat-entropy chart, and is the value in B.T.U.'s of steam at the pressure and temperature considered ;

where h_1 , is the heat content in B.T.U.'s of the feed-water entering the economizer. As the Fahrenheit temperature scale is the one usually adopted, the value of h_1 is found by subtracting 32 from the temperature in degrees F. of the economizer water ;

where C , is the calorific value of the fuel as fired, expressed in B.T.U.'s per lb.

The efficiency thus calculated represents the heat absorbed by the combined unit or plant, expressed as a percentage of the heat content of 1 lb. of coal. The B.T.U.'s absorbed per lb. of coal is the value $E \times (H - h_1)$ in the foregoing equation. As stated previously the boiler, superheater, and economizer are sometimes considered separately, and in certain instances the efficiency of the furnace is also expressed as a separate item. Furnace efficiency, which has already been referred to, may be defined as the ratio of the heat available for absorption by the boiler unit to the heat in the coal, and may be calculated as follows—

$$\text{Furnace efficiency} = \frac{E \times (H - h_1) + 0.24W (T_2 - T_1)}{C}$$

where $E \times (H - h_1)$ and C have the same values as in the previous equation and $0.24W (T_2 - T_1)$ is the heat content of the flue gases per lb. of coal consumed. This latter part of the equation will be discussed when considering the heat losses in the flue gases. If each section of the boiler or boiler plant is to be considered separately, the efficiency of the boiler alone is calculated as follows—

$$\text{Boiler efficiency} = \frac{E \times (H - h_2) \times 100}{C} \quad . \quad . \quad . \quad (1)$$

The values of E and C are as before, but h_2 is the heat content of the water entering the boiler, that is, the water leaving the economizer, and is found by subtracting 32 from the temperature in degrees F. of the economizer outlet water. H in this instance is the heat content of the saturated steam at the given pressure.

The efficiency due to superheating the steam is found by multiplying E by the heat absorbed in the superheater per lb. of steam. In other words, the superheater efficiency gain equals—

$$\frac{E \times (Hp - Hs) \times 100}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In this case Hp and Hs are the total heat contents per lb. of superheated and saturated steam respectively. The values in B.T.U.'s per lb. can be read as before, i.e. from standard steam tables or heat-entropy charts.

The gain in efficiency due to heating the feed-water in an

degrees F. of the stack gases, or the temperature of the gases leaving the economizer. T_1 is the temperature in degrees F. of the air entering the grates. W is the weight of the flue gases in pounds per pound of coal consumed. The value of W can only be accurately calculated from a knowledge of the composition of the coal and an analysis of the flue gases. Various formulae are given in treatises on boiler-house chemistry for calculating the value of W , but few of them are anything like accurate. Certain of them attempt to determine the weight of flue gas formed, per pound of coal consumed, from the percentage value of the CO_2 appearing in the flue gases. These, while possibly giving approximate results for one particular class of coal and other definite conditions, cannot be applied in any other case. Others again attempt to estimate flue gas losses or flue gas weight per pound of coal without taking into account the hydrogen or the moisture content in the fuel, and therefore the only formulae which should be used for computing flue gas losses and weights are those in which account is taken of all the constituents appearing in the gases.

Carbon, as we have seen, burns to either CO_2 or CO , and will therefore appear in the dry flue gases in the same weight as in the original coal, with the exception of the usually very small quantity carried over as unconsumed carbon in the ash. The hydrogen burns to H_2O , and at the temperatures met with in practice is carried away in the form of steam or water vapour in conjunction with the steam or vapour from the evaporation of the moisture in the coal. Therefore assuming the complete combustion of the hydrogen and for the present neglecting the sulphur constituent, the only gases which can be determined by practical boiler-room methods of gas analysis are carbon-dioxide, carbon-monoxide, oxygen, and nitrogen. It is usually agreed that a flue gas analysis gives the percentage volume of the constituent gases on a dry basis, therefore it is a simple matter converting the percentage volume of CO_2 , O_2 , CO , and N to a basis of percentage weight, from which the weight of dry gas per pound of carbon can be calculated.

If the hydrogen content of the coal is perfectly consumed, the amount of steam or water vapour appearing in the flue gases will have a constant weight, irrespective of the value of the excess air, and therefore if the hydrogen content of the coal is known, the weight of steam or water vapour

produced by the combustion of the hydrogen can be readily determined. Another point very often overlooked in calculating total flue gas weight is the steam or water vapour produced from the evaporation of the moisture present in the coal, and though the loss from this source may appear as an item in a heat balance, the weight of this steam or vapour is often neglected when determining total gas weights.

From what has now been said, it should be obvious that the only method of arriving at flue gas weights and losses with any degree of accuracy is by considering each item separately, as set out above.

The methods of computation to be described involve a knowledge of the composition of the coal and flue gases, necessitating an analysis of the fuel as well as the flue gases. In many stations, due principally to lack of organization and the resulting absence of the necessary apparatus, it is impossible to obtain the required data and at the best the individual losses in these plants can only be guessed at.

The following formula based on relative densities and the analysis of the dry flue gases can be used for calculating the weight of the dry products of combustion per pound of carbon—

$$W_c = \frac{11\text{CO}_2 + 8\text{O}_2 + 7(\text{N}_2 + \text{CO})}{3(\text{CO}_2 + \text{CO})}$$

where W_c = weight in lbs. of dry products of combustion per pound of carbon ;

and CO_2 , O_2 , CO , N_2 = constituents of gases as determined by analysis.

It should be noted that the foregoing formula gives the weight of gases per pound of carbon, therefore to obtain the dry gas weight per pound of coal consumed the foregoing formula must be multiplied by the carbon content of the coal as fired expressed as a fraction, minus carbon in ash. Another corrective factor must also be introduced if the sulphur content of the coal is appreciable. The factor for correcting for the sulphur equivalent is in the ratio of the weights of the products of combustion of carbon and sulphur, and where a heat balance is required to a high degree of accuracy, the dry products of combustion per pound of coal must be corrected accordingly. Ordinarily, however, if the sulphur content of the coal is low, the correction can be neglected without the

introduction of any appreciable error and the weight of the dry products of combustion per pound of coal can be safely calculated from—

$$W_c = \frac{11\text{CO}_2 + 8\text{O}_2 + 7(\text{N}_2 + \text{CO})}{3(\text{CO}_2 + \text{CO})} \times C$$

where W_c = weight in pounds of dry products of combustion per pound of COAL ;

C = carbon content of coal ("dry" or "as fired" depending on basis selected) expressed as a fraction.

Remainder of symbols as in previous equation.

The following example will illustrate the method of computation. Assume the analysis of the flue gases to be—

$$\begin{aligned}\text{CO}_2 &= 14.0 \text{ per cent} \\ \text{O}_2 &= 4.8 \quad ,, \\ \text{CO} &= 0.2 \quad ,, \\ \text{N}_2 &= 81.0 \quad ,,\end{aligned}$$

Further assume that the carbon content of the coal as fired is 60.00 per cent. Total ash, 10.00 per cent. Carbon in ash, 15.00 per cent.

Then actual carbon consumed per pound of coal is,

$$0.60 - 0.015 = 0.585.$$

Substituting the values in the equation, we have—

$$\frac{(11 \times 14.0) + (8 \times 4.8) + 7(81.0 + 0.2)}{3(14.0 + 0.2)} \times 0.585$$

= 10.45 lbs. of dry flue gas per pound of coal consumed.

Assuming that the calorific value of the coal as fired was 10,500 B.T.U. per pound, air temperature 70° F., and flue gas temperature 350° F., then the heat loss in the dry flue gases per pound of coal would be—

$$\begin{aligned}& .24 \times 10.45(350 - 70) \\ & = 703 \text{ B.T.U.'s} \\ & = 6.69 \text{ per cent.}\end{aligned}$$

It should be clearly understood that this is the loss in the dry gases, not the loss in the total gases.

Fig. 33 shows the flue gas losses in B.T.U.'s per pound of coal consumed for various values of CO_2 and gas outlet temperatures for one particular case. We have seen that

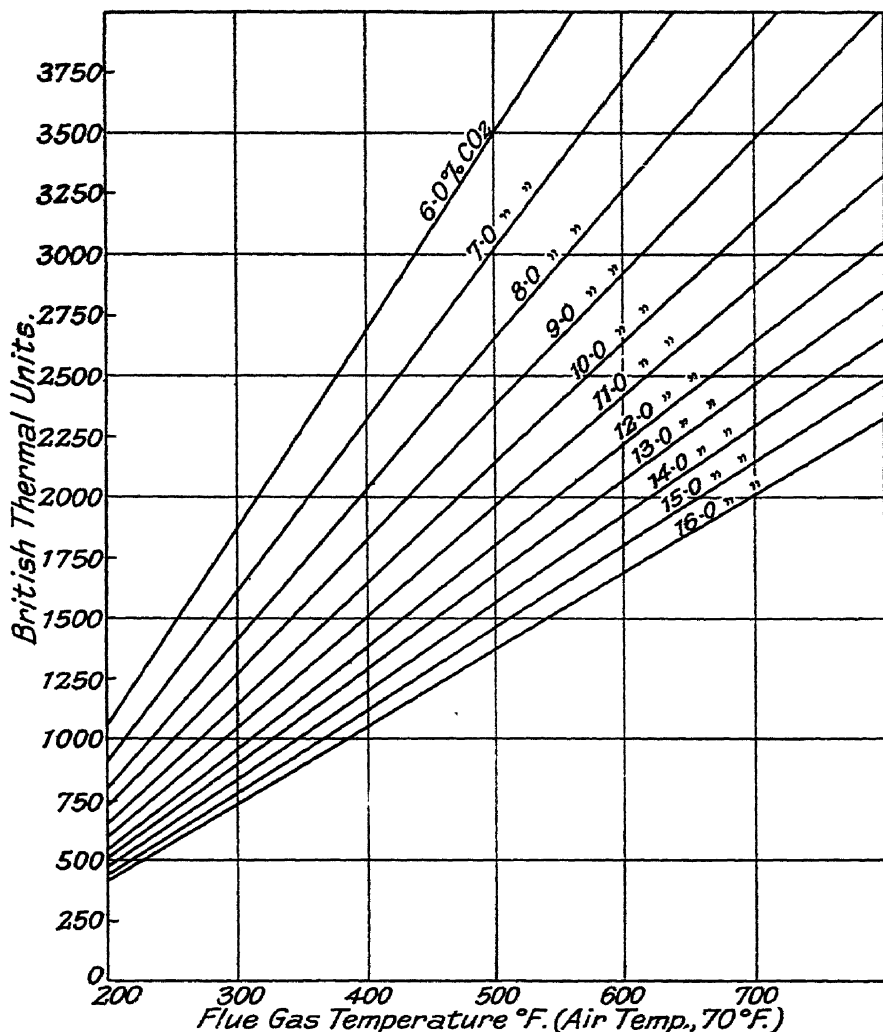


FIG. 33.—FLUE GAS LOSSES IN B.T.U.'S PER LB. COAL, FOR VARIOUS CO_2 VALUES.

$0.24W (T_2 - T_1)$ equals the heat per lb. of coal carried away by the flue gases, therefore if T_2 be measured at the economizer gas inlet, the equation will also be equal to the heat passing into the economizer, and $0.24W (T_3 - T_1)$ will equal the heat

passing out of the economizer, T_3 being the gas outlet temperature. The difference will represent the heat taken up by the water. Similarly, if t_1 equals the economizer inlet water temperature, and t_2 equals the outlet water temperature, then t_2 minus t_1 equals the heat increase per lb. after passing through the economizer. These symbols can be arranged as follows in the form of a heat balance formula, from which the efficiency of the economizer as a unit for the transference of heat can be judged, and its condition of cleanliness determined—

$$0.24W (T_2 - T_1) - 0.24W (T_3 - T_1) = E \times (t_2 - t_1)$$

where E has the same value as in the previous equations.

It has already been stated that the combustion of the hydrogen in the coal results in the production of steam or water vapour in the flue gases. Therefore the loss from this source will be the sensible heat above the temperature at which the air and coal was admitted to the furnace, plus the latent heat of steam at approximately atmospheric pressure. The total heat per pound can be ascertained directly from steam tables and knowing the percentage of hydrogen in the coal and assuming the complete combustion of the hydrogen, the heat loss per pound of coal consumed can thus be calculated.

The heat loss due to the hydrogen constituent may also be calculated from the following formula—

$$\begin{aligned} &\text{Loss in B.T.U.'s per pound of coal consumed} \\ &= H_2 9[(212 - t) + 970.4 + .48(T - 212)] \end{aligned}$$

where H_2 = percentage of available hydrogen in the coal ;

t = temperature deg. F. of air or coal ;

T = temperature deg. F. of flue gases ;

970.4 = latent heat of steam at atmospheric pressure ;

0.48 = mean specific heat of steam at atmospheric pressure.

As an example, assume the available hydrogen to be 4.00 per cent, air temperature 70° F., and flue gas temperature to be 350° F., then the loss due to the combustion of this hydrogen, expressed in B.T.U.'s per pound of coal consumed equals—

$$0.04 \times 9[(212 - 70) + 970.4 + .48(350 - 212)] = 520 \text{ B.T.U.'s.}$$

Expressed as a percentage of the heat value per pound of

coal, assuming the same calorific value as in the previous example, we have—

$$\frac{520 \times 100}{10,500} = 4.9 \text{ per cent.}$$

The weight of steam or water vapour produced by the combustion of the hydrogen or the amount of air used can be calculated by the methods described in the section dealing with the chemistry of combustion.

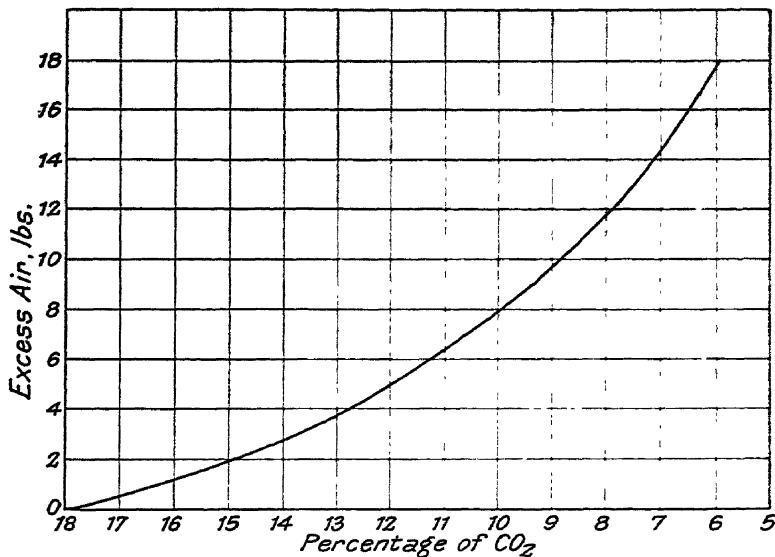


FIG. 34.—EXCESS AIR LBS.

As we have seen, excess air is one of the greatest sources of excessive flue gas loss, since it reduces the percentage of CO₂, increases the products of combustion, and therefore reduces the efficiency. Fig. 34 shows for one particular case the weight of excess air per pound of fuel for various values of CO₂. The following example will show the effect of excess air. Assume two specific cases (a) and (b)—

(a) CO₂ = 15.0% = 2 lbs. excess air per lb. of coal.

(b) CO₂ = 8.0% = 13.75 lbs. excess air per lb. of coal.

If the flue gas final temperature be assumed as 400° F., and the temperature of the air entering the grates as 60° F., then the loss in the case of (a)—

$$0.24 \times 2 (400 - 60) = 163 \text{ B.T.U.'s.}$$

And in the case of (b)—

$$0.24 \times 13.75 (400 - 60) = 1,122 \text{ B.T.U.'s.}$$

(0.24 = specific heat of air.)

On the other hand, a deficiency in the air supply will also result in a loss due to the carbon in the coal burning to CO instead of CO₂. This loss in a fairly well operated plant is negligible, but on the other hand it may assume quite appreciable proportions. The loss in B.T.U. per lb. of coal consumed can be calculated from the following formula—

$$C (10150) \frac{\text{CO}}{\text{CO}_2 + \text{CO}}$$

where CO and CO₂ are the volumes of these gases expressed as fractions and C is the total carbon in the coal less carbon in ash. In practice, the flue gas analysis determined by the Orsat apparatus will give a very good indication of the flue gas losses both as regards excess air and completeness of combustion. The following analysis would be representative of good practice—

CO ₂	.	.	.	.	.	14.00%
O ₂	.	.	.	.	.	4.80%
CO	.	.	.	.	.	0.00%
N etc.	.	.	.	.	.	81.20%

As has been explained, to calculate to a fair degree of accuracy the flue gas losses, a thorough volumetric analysis must be made and the physical properties of each gas taken into consideration—

O ₂ specific heat	.	.	.217	CO specific heat	.	.	.243
N ₂ „ „	.	.	.247	CO ₂ „ „	.	.	.21
H ₂ „ „	.	.	3.42	H ₂ O (vapour) spec. heat	.	.	.48
Air „ „	.	.	.24	H ₂ O (water) „ „	.	.	1.00
Flue-gases spec. heat	.	.	.24	(average)			

The following (Table XII) shows the density of gases at 32° F. and 29.92 ins. of mercury.

The previous remarks concerning the uselessness of certain formulae given for the calculation of flue gas losses, apply equally to many formulae offered for the calculation of air quantities involved in combustion.

It should be obvious from what has been said that the oxygen and consequently the air supplied for combustion, neglecting the moisture contained in the air, can only be computed by determining the weight of the dry gases

TABLE XII

DENSITY OF GASES AT 32° F. AND 29.92 INCHES MERCURY

Gas.	Chemical Symbol.	Relative Density. Hydrogen = 1.	
		Exact.	Approximate.
Oxygen	O	15.87	16
Nitrogen	N	13.92	14
Hydrogen	H	1.00	1
Carbon Dioxide	CO ₂	21.83	22
Carbon Monoxide	CO	13.89	14
Methane	CH ₄	7.95	8
Ethane	C ₂ H ₆	14.91	15
Acetylene	C ₂ H ₂	12.91	13
Sulphur Dioxide	SO ₂	31.96	32

produced from the combustion of the carbon (corrected for sulphur), and the water vapour formed from the combustion of the hydrogen.

Therefore the dry air supplied per pound of coal equals the dry products per pound from the combustion of the carbon, plus the water vapour from the combustion of the hydrogen, minus the actual carbon per pound of coal consumed, i.e. total carbon minus carbon carried over in the ash.

The ratio of the air supplied to the amount theoretically necessary or, in other words the percentage of excess air, can only be determined by comparing the dry air actually supplied per pound of coal, to the theoretical quantity determined from the constituents of the coal as found by ultimate analysis. It is in this direction that there is greater room for co-operation between the boiler and stoker manufacturers and the makers of boiler-room efficiency instruments, for until we can accurately measure the amount of air being supplied for the process of combustion, the boiler-room crew will always be working in the dark. Our present instruments for boiler-room control advise the operating staff of inefficient conditions *afterwards*, but if accurate air metering apparatus could be designed and built, and some form of automatic instrument could be devised for sampling, analysing, and recording the percentage of carbon and hydrogen in the fuel; and if our air-mixing arrangements were 100 per cent efficient, the combustion of coal would become what it should be, an accurate chemical process.

As has been stated, the only method of accurately calculating the air quantities involved in combustion is by an analysis of the gases forming the products of combustion. In daily operation where approximate values will often help considerably towards obtaining the correct conditions, the amount of dry air supplied per pound of coal can be estimated from the following formula—

$$A = \frac{3.036N_2}{(CO_2 + CO)} \times C$$

where A = dry air in pounds per pound of coal;

CO_2 , CO = constituents of these gases in flue gas, by volume;

c = carbon content of coal expressed as a fraction,
and corrected if desired for carbon in ash.

In certain cases, depending upon the class of coal used, the

percentage of excess air can be roughly estimated from the indications of a CO_2 indicator or recorder by the following formula—

$$\text{Excess air per cent} = \frac{20.7 - \text{CO}_2}{\text{CO}_2} \times 100$$

where CO_2 is the observed percentage of that gas as recorded by the instrument.

Loss Due to Evaporation of Moisture. Almost invariably the coal fed to the boiler furnaces is in a very wet condition. In some cases the moisture percentage may be as much as 25 per cent or more. This moisture has to be evaporated and superheated, and finally escapes as highly superheated steam at atmospheric pressure with a total temperature equivalent to the final temperature of the flue gases. The method of calculating this loss is best explained by an example. Assume the total moisture content to be 10 per cent and the initial and final temperatures to be 60°F. and 400°F. , then the total heat per lb. of steam in the flue-gases equals 1,217 B.T.U.'s, or a loss of approximately 122 B.T.U.'s per lb. of coal. It is, however, often an advantage to feed the coal to the grates in a wet condition, due to the fact that the moisture tends to bind the coal and make it burn more evenly on the grate.

Loss Due to Unburned Carbon. The loss due to unburned carbon in the ash may assume serious proportions if the fires do not receive the requisite amount of attention. Under good conditions this loss should not exceed 1 to 2 per cent. In calculating this loss it is assumed that all the combustible carried over in the ash is pure carbon with a heat value of 14,500 B.T.U.'s per lb. The ash percentage should be taken as that found from the proximate analysis. It would be erroneous to assume the weight of ashes removed from the ash-pits to represent the ash percentage in the coal, because under modern draught conditions quite a large quantity of the finer ash is blown or drawn up the stack. The loss due to unburned carbon in the ash is found as follows—

$$14,500 \times AC$$

where A = fraction of ash in the coal from analysis

C = fraction of carbon in ash.

Loss Due to Radiation. The loss due to radiation in a modern well-maintained boiler plant, with iron cased units and efficiently lagged steam surfaces, should not exceed 4 per cent,

but the loss from this source in the older plants is enormous. One has only to see the state of the boilers and steam piping arrangements in these plants to realize the truth of this. The best method of determining the radiation losses is by checking the coal consumption necessary to keep a boiler just under working pressure, but not supplying any of the steam for the commercial load.

Comparative Evaporation. The evaporation of so many pounds of water per lb. of coal from and at 212° F. has, in the past, formed one basis for comparison of boiler performance. This value does not give a comparative figure, and it is now customary in the larger undertakings to expand this figure to give the equivalent evaporation per 10,000 B.T.U.'s in the coal. The evaporation from and at 212° F. is calculated by multiplying the actual evaporation by a factor. This factor of evaporation, as it is termed, is found from the following formula—

$$F = \frac{H - h_1}{L}$$

where H = total heat in steam in B.T.U.'s per lb.

h_1 = total heat in economizer inlet water in B.T.U.'s per lb.

L = latent heat of steam = 970.4.

The equivalent evaporation per 10,000 B.T.U.'s then equals—

$$W \times \frac{10,000}{C}$$

where W = evaporation from and at 212° F.

C = calorific value of the coal in B.T.U.'s per lb.

Auxiliaries. In some instances the power supply for the boiler-room auxiliaries is calculated as an item of the heat balance. If the auxiliaries are electrically driven the mistake must not be made of multiplying the registered kilowatt-hours by the B.T.U. equivalent (3,414). In a manufacturing concern, where the energy is purchased from a supply authority, this method is quite correct, but in the case of a power station the heat cost of auxiliary energy in B.T.U.'s per kilowatt-hour must first be determined and the kilowatt-hours registered for the boiler-room auxiliaries multiplied by this value. Where a portion of the auxiliaries are steam-driven, the heat consumption of these units can be determined from indicator diagrams

in the case of reciprocating pumps, etc., and for small turbines the nozzle area, pressure, and specific volume of the steam before the nozzle are the necessary factors from which the performance of these small units can be approximately calculated. The problem of auxiliary drives is more fully dealt with later.

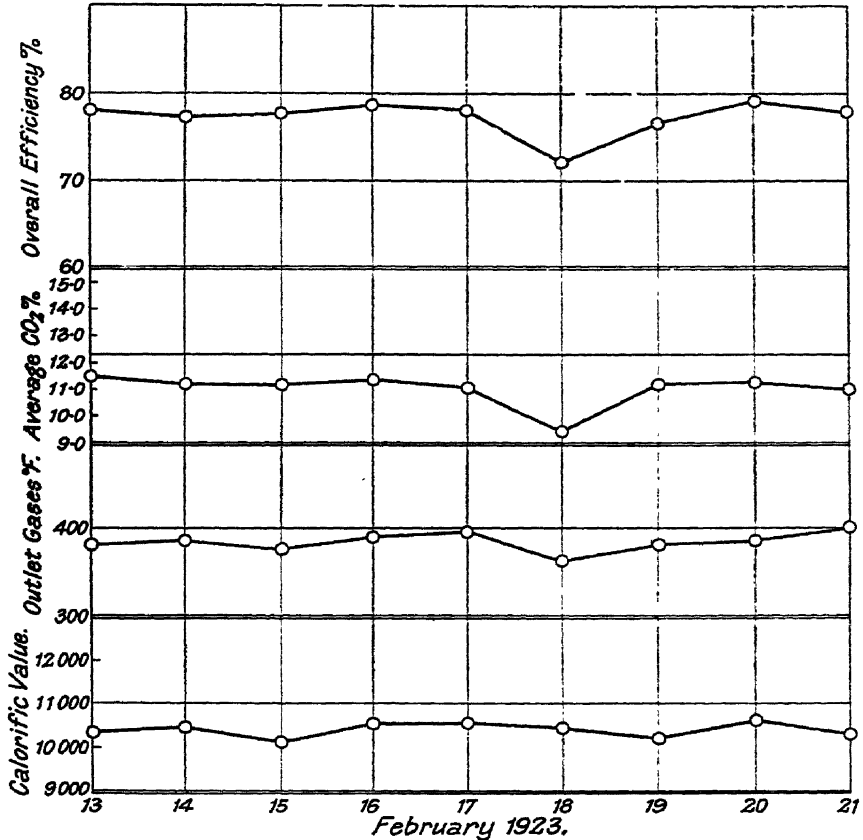


FIG. 35.—DAILY OPERATING STATISTICS :
No. 1—BOILER ROOM.

Tabulation of Operating Results. Efficiency control is not simply a matter of reading instruments and calculating the various efficiencies and losses. Each item of the heat balance statement must be investigated and immediately a decrease in efficiency and consequent increase in the losses take place, the cause must be found and remedied. The experienced engineer in charge should, however, be able to detect any

falling off in efficient performance from the indications given by the boiler-room instruments, but for the other members of the power station staff, a record of performance is necessary, as it brings home to them in a concise manner just what results are being obtained. At the end of each shift, or twenty-four hours as the case may be, the principal items of the heat balance should be calculated and tabulated in the following manner. Table XIII. The values inserted in the heat balance statement in Table XIII are actual values from the operating results of a large modern power station, and are representative of very efficient boiler-room plant performance. Another method of keeping a record of plant performance consists in logging the results in graphical form, thus the trend of the various efficiencies from day to day are readily noticeable. An example of such a system is shown in Fig. 35. And in Table XIV is shown an example of the tabulation of the boiler-room statistics.

Load Factor, etc. In the best of modern boiler-rooms, provided with the best of modern instruments, the daily operating results are influenced by three factors, viz.: the variability of the fuel, load factor, and the human element. The question of the variability of the fuel has already been referred to in an earlier part of the book, but a decrease in efficient operation when the coal being fed to the furnaces is varying in quality, is not so much due to the variance of the quality of the coal as to the reluctance of the average fireman to adapt himself to the changing conditions. Allowing for the varying grades of coal, efficiencies of 80 to 85 per cent under test conditions ought not to be hard to obtain. Under normal conditions the boiler-room efficiency over a week's running, and taking into consideration the effect of the week-end, ought not to be less than 75 per cent in the case of the more modern plants. Undoubtedly the question of load factor, with its resultant banked fires and lightly loaded steaming units, enters into the results obtainable under operating conditions, compared with the figures which can be obtained under test conditions, but load factor is too readily put forward as an excuse for low operating efficiencies. "The price of efficiency is eternal vigilance," and if the boiler-room crew will exert themselves sufficiently to maintain a high CO_2 , and the correct draught conditions on the lightly loaded steaming units, it will be found that test figures can be very closely approached. Again, the engineers responsible for the boiler-room

TABLE XIII

BOILER-ROOM HEAT-BALANCE

Date

PER POUND OF COAL

	B.T.U.s.	%		B.T.U.'s	%
To Calorific Value of Coal as Fired	10,500	100.00	By Heat Transfer in Boilers	6,327	60.26
			" " Superheaters	1,065	10.15
			" " Economizers	1,035	9.86
			" " Combined Plant	8,427	80.27
			" Loss in Dry Flue Gases	754	7.18
			" " in Moisture in Coal	130	1.24
			" " Due to Combustion of Hydrogen	504	4.80
			" " Incomplete Combustion (CO)	158	1.50
			" " in Combustible in Ash	210	2.00
			" " in Radiation	294	2.80
			" " in Moisture in Air, Heat in Ashes, and unaccounted for	23	0.21
TOTALS	10,500	100.00	TOTALS	10,500	100.00

TABLE XIV

No. 1 Boiler-Room.

Date

Shift.	Total Coal (consumed, lbs.	WATER.						Average Calorific Value of the Coal as Fired.	Roller House Efficiency.	Turbine Room Efficiency.	Station Thermal Efficiency.	Cost of Evaporating 10,000 lbs. of Water.
		(Condensate, lbs.	Make-up Water, lbs.	Total Water, lbs.	Make-up Water, per cent of Total.	Actual lbs of Water evaporated per lb. of Coal.	Equivalent Evaporation from 212° F. at 100 lbs. B.P. in Coal.					
12.0 mn.-8.0 a.m.												
8.0 a.m.-4 p.m.												
4.0 p.m.-12.0 mn.												
12.0 mn.-12.0 mn.												

Time.	No. of Boiler Blown Down.	Inches Blown Down.	Boiler or Economizers Fired.	Safety Valves Blowing, Econo- mizer Beliefs Lifting, Leaky Drains, Traps, etc.						
					Load Coal	=	lbs.	Banking Coal	=	lbs.
					Kw.-hrs. Induced Draught Fans =					
					" Forced Draught Fans =					
					" Stoker Drives =					
					" Electrical Feed Pumps =					
					Boiler-Room Kennedy Factor =					

operation are too often inclined to look with suspicion upon figures obtained under test conditions, and it is often remarked that these figures are of no use as an indication of what the plant should do under daily operating conditions. Granting the small effect of load factor there is, or should be, in the average power station boiler-room, no difference between test and operating conditions. As far as is possible consistent with reliability of service, no more plant should be steaming than is absolutely necessary. The load to be carried on a station can be fairly well anticipated from day to day, and the factor of reliability of service in the boiler-room should be limited to one boiler. That is to say, if the turbine-room steam demand is equivalent to six boilers, seven boilers should be on the range. A kilowatt load-indicator, electrically operated from the station control-room should be installed in each boiler-room, so that the boiler-room engineer can see at any instant the load on the station. An efficient telegraph and loud-speaking telephone service is another necessity, and the load indicators and telegraph and telephone services should work in conjunction with a Klaxon horn; there is then no excuse for ignorance of changing conditions. The control-room engineer, of course, must see that the boiler-room is kept fully posted with every change of load. The greatest factor affecting the operating efficiency of the boiler-room is undoubtedly the human element, for even if it should be possible for the best designers to arrange a combination of heating and recuperative surface, which will absorb 85 per cent of the heat offered to it from the furnace, it still depends upon the boiler-room crew, more than anything else, whether this figure will be obtained in practice.

The principal factors of the boiler-room staff are the superintendents, or boiler-room shift engineers, and these men must be enthusiasts. Short interesting lectures, they need not be highly technical, should be given to the firemen, and every endeavour made to make the men keenly interested in their work. The various sources of loss should be explained to them, and the effect of those losses on the coal bill. Charts, showing the values of the different losses and efficiencies, should be framed and hung in the boiler-room. The firemen should be taught the functions and the meaning of the instruments and their indications, and how, from these indications and a reference to the charts, the best combination of conditions can be arrived at. There is a lot of work done in this direction

in America, where one watch is pitted against another in the production of efficient results and a bonus paid on these results. It is not intended to deal in this book with power station maintenance and repair, but it goes without saying that a boiler-room, to be efficiently operated, must be kept in a high state of repair, in short, the various parts must be steam-tight, water-tight, and gas-tight. In fact, it is impossible either to maintain or improve the efficiency until all obvious repairs have been carried out.

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CHAPTER VI

BOILER FEED-WATER

THE efficient operation of a power station may be influenced to a considerable extent by the nature of the water used for make-up feed⁴ purposes. The ideal feed-water for steam-raising purposes should neither contain solids in suspension or solution, nor dissolved gases. It is impossible to attain this ideal in practice, but the importance of as pure water as possible cannot be over-estimated, more so in view of the present-day tendency towards large boiler units. The question of pure make-up feed-water is only second in importance to that of the fuel.

Make-up Water. Providing that condenser leakage is kept to a negligible value, oil-free de-aerated condensate from the turbines is the only water that should be fed to the boilers without undergoing treatment. All other supplies used for boiler feeding purposes are more or less contaminated and, if fed direct, will inevitably cause trouble through corrosion, erosion, or the deposition of scale. From this it will be seen that not only must the make-up feed-water be treated, but it must also be kept to as low a value as possible, and this can only be done by strict attention to all sources of steam or condensate losses, such as unnecessary blowing down, blowing off, range traps and drains, turbine drains, and feed-water heater, and V-notch meter overflows. To prevent the percentage of make-up feed-water reaching excessive values, all range drains and traps, turbine drains, and all overflow pipes which are likely at times to carry condensate should be connected to one or more common headers. These headers, which should be at a level to permit of the drains, etc., discharging into them by gravitation, can be of sufficient capacity to hold a reserve supply of water, which can be periodically lifted to the boiler-room hot wells by a pump or other means.

It is understood that scale on the plates and tube surfaces of a boiler or economizer will, to an extent depending upon the nature of the scale, affect the heat transmission and thus decrease the boiler efficiency. The loss due to using untreated scale forming or corrosive water as make-up feed is principally represented by the extra coal consumed, the cost of cleaning,

re-tubing and repairing boilers, and the cost of extra stand by plant due to the necessity of frequent cleaning, re-tubing, etc.

Treatment of Water. It is not intended to deal in this book with the various appliances for producing pure make-up feed water, but rather to deal with the various tests which the power station engineer must be capable of carrying out to ensure that the water being fed to the boilers is not of a harmful nature. The production of softened water suitable for boiler feeding purposes is accomplished *by one of the following methods: (a) chemical treatment; (b) distillation; (c) zeolite treatment; and (d) treatment for the prevention of corrosion. The method of chemically treating water has not changed much during the last fifty years. Hydrate of lime, either as lime water or milk of lime, is still the most economical and practicable means of converting the bicarbonates to carbonates or hydrates, absorbing carbon dioxide and neutralizing acids. Treatment by means of soda is still the method most widely used for converting the sulphates, chlorides, and nitrates to carbonates. Before a water can be accurately and scientifically treated the chemical composition of the impurities it contains must be known. If a river is the source from which the water is drawn, the nature of the country through which it flows and effluents from manufacturing concerns, sewage works, etc., situated on its banks must be investigated. The proportion of impurities contained in the water will vary with the state of the river and in power stations where the crude water for treatment is drawn from such a source, analyses must be regularly carried out. It is not proposed to describe the method of making a complete analysis of a water, as this can only be carried out by a skilled chemist or engineer trained in this class of work, but a knowledge of the impurities usually contained in a natural water, and their effect on the boilers will be of interest, especially to those shift engineers whose duty it is to make daily hardness and alkalinity determinations for the adjustment of lime and soda ash in connection with water softening plant. The following are the impurities usually found in all natural waters.

Calcium Carbonate (CaCO_3). This is a salt of the metal calcium, derived from chalk or limestone, and is the most common of all the scale or deposit forming constituents. In the form of carbonate it is only soluble to the extent of two or three grains per gallon, but if the water contains even a small

quantity of sodium chloride or an appreciable amount of vegetable matter, the solubility of this monocarbonate of calcium is increased. It is the presence of chloride of sodium that often prevents complete softening of a crude water. CaCO_3 is non-corrosive in boilers, and also tends to neutralize the acids produced by the decomposition of corrosive constituents if they should be present. The insolubility of CaCO_3 is further utilized in water softening. Calcium chloride (CaCl_2) and calcium sulphate (CaSO_4) cannot be precipitated by themselves, but by the addition of sodium carbonate (Na_2CO_3); these salts are decomposed, forming CaCO_3 and precipitating out. In all natural water, carbonates are present in the form of bicarbonates which are highly soluble. Calcium bicarbonate is precipitated by taking away from it the extra molecule of CO_2 , this can be done by heating the water to a temperature not less than 170°F . or by treating it with calcium hydrate (Ca(OH)_2 slaked lime). The calcium hydrate taking up the molecule of CO_2 , forming CaCO_3 and precipitating out, with the exception of course of the two or three grains per gallon which water will hold in solution.

Calcium Sulphate (CaSO_4). The sulphate of calcium is a very objectionable constituent in feed-water, and unless it is completely removed in the softening plant boiler trouble due to scale will ensue. Its solubility is greatest at about 95°F ., at which temperature it is soluble to the extent of about 170 grains per gallon. At temperatures above 212°F . the solubility rapidly falls and, at the temperatures existing in modern water-tube boilers, it is practically insoluble. When precipitated in the boiler drum or tubes it remains fast as soon as it comes into contact with the metal, and is not disturbed or shifted by the convection currents, which keep the softer carbonate precipitate so long in suspension. It forms a crystalline scale of very great hardness, depending upon the temperature to which it has been subjected while in contact with the plate. Carbonate scale may be kept comparatively soft and easily removed if the boiler is allowed to cool before draining off the water at inspection periods.

CaSO_4 is removed from a crude water by the addition of Na_2CO_3 , the soda (Na_2O) combining with the SO_3 of the sulphate of lime, forming sulphate of soda (Na_2SO_4) which in boilers is soluble, neutral and inert. The CO_2 of the soda ash combines with the CaO of the calcium sulphate, forming a precipitate of CaCO_3 , or chalk.

Calcium Chloride (CaCl_2). Calcium chloride is extremely soluble in water at all temperatures, but is only occasionally present in natural waters, and then not to any important extent. Owing to its solubility its presence in the boiler will not cause scale or deposit, but if present in solution with magnesium sulphate (MgSO_4) trouble may occur. These two salts though harmless when separate will, under the above conditions, react with each other, forming calcium sulphate and magnesium chloride, the CaSO_4 forming the hard scale already referred to, and the MgSO_4 decomposing and liberating hydrochloric acid with consequent corrosion of the boiler plates. CaCl_2 is removed from the crude water by the addition of Na_2CO_3 , the resulting products of the reaction being CaCO_3 which is precipitated, and sodium chloride (NaCl).

Calcium Nitrate. Calcium nitrate is very seldom found in a natural water. It is very soluble and by itself will not cause scale or corrosion, but if present in the boiler with MgSO_4 or Na_2SO_4 a reaction may occur precipitating scale forming CaSO_4 . At high temperatures and high degrees of concentration there is also the probability of decomposition with the liberation of corrosive acid. In softening plants it is precipitated as CaCO_3 by means of Na_2CO_3 in a similar manner to the sulphate and chloride.

Magnesium Carbonate (MgCO_3). This salt is found in a natural water due to the filtration of rain and spring water through ground containing dolomite limestones. Like the carbonate of calcium it is always present in the crude water in the form of bicarbonate, also the bicarbonate is much more soluble than the carbonate. MgCO_3 is not detrimental in a boiler with the exception, of course, that, like all impurities harmless or otherwise, it increases the concentration. Under boiler conditions it is possibly present in the form of magnesium hydrate. The carbonate salts of calcium and magnesium are commonly termed "temporary hardness," because they are both precipitated to a considerable degree by heating the water, and where a supply of exhaust steam is available, and the make-up water chemically treated, a hot process water softener should invariably be installed. MgCO_3 is removed from the crude water by treatment with $\text{Ca}(\text{OH})_2$ (slaked lime). In boiler deposit and scale there is generally a small quantity of magnesium oxide (MgO) present although none was contained in the original water; this is due to the decomposition of the hydrate at high temperatures.

Magnesium Sulphate (MgSO_4). Magnesium sulphate is very soluble in water at all temperatures, its solubility increasing with increase of temperature. Owing to this fact it is not precipitated if present in a boiler and is generally looked upon as a neutral impurity. There is the probability, though, that if chlorides or nitrates are also present, corrosion is likely to result, due to reaction with the magnesium sulphate liberating acids. Under the high pressures at which modern water-tube boilers work, magnesium sulphate and calcium carbonate, if present in the boiler together, will react upon each other, forming magnesium carbonate and the scale forming calcium sulphate. Magnesium sulphate is removed from a crude water by treatment with caustic soda, which is formed, in the combined lime and soda process softening plants, by the interaction of the slaked lime and sodium carbonate.

Magnesium Chloride and Magnesium Nitrate. Both these salts are very objectionable impurities; they are very soluble and will therefore not be precipitated in their original form if present in the boiler, but due to decomposition by reacting with other salts and the metal of the boiler, corrosive acids are liberated. The removal of these salts from a natural water is effected by treatment with lime and soda ash. Other impurities which may be found but which are not considered troublesome, except under certain circumstances, are silica, ferrous salts, alumina, and manganese. These salts are removed by treatment with lime and soda ash. Salts of the alkali metals are nearly always present, and they can only be effectively removed by distillation. They are not scale forming or injurious to the boiler except that under a high degree of concentration, priming and foaming may result.

Free Acid and Pollution. Power stations are, as a rule, situated in industrial districts and consequently the crude make-up feed-water, whether drawn from a well or a river, may contain other detrimental impurities besides the natural mineral constituents. Acid waters may be derived from the effluents from steel and iron works, and dye, galvanizing, and chemical works, and in the neighbourhood of gas works pollution, due to ammonium sulphate, may be caused. Natural waters even before contamination in industrial areas may show slight acidity from peaty acids.

Unless the make-up feed-water is carefully treated pollution from any of these works' effluents will result in pitting or

corrosion in the boiler. A lime and soda process water softening plant is shown in Fig. 36.

Corrosion. Corrosion is a source of great trouble, particularly in boiler feed ranges and steel-tube economizers. In a natural water many of the mineral constituents have a marked effect on the rate of corrosion, these as we have seen are the chlorides and nitrates of calcium and magnesium. In the

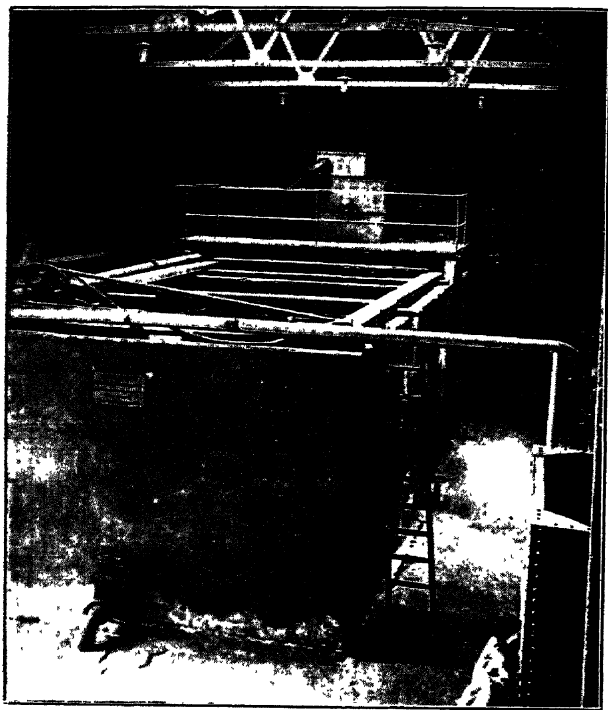


FIG. 36.—PATERSON'S WATER-SOFTENING AND PURIFYING PLANT.

past these impurities were looked upon as the direct cause of corrosion, and it is only within recent years that the effect of dissolved gases in an otherwise pure feed-water have received the serious attention which they merit. Water if exposed to the atmosphere will absorb the constituent atmospheric gases, the amount absorbed depending upon the proportion of the particular gases present, the temperature, and the solubility of the gases at that temperature. It has been proved that the particular gases involved are oxygen and carbon dioxide. (The proportion of these gases in

atmospheric air has already been discussed in a previous chapter.) It has also been proved that with practically any natural water corrosion stops if the oxygen is removed. If the feed-water contained only oxygen in solution, then only iron oxide would be formed in the feed-water ranges. A well-known authority on boiler-room chemistry proved in the

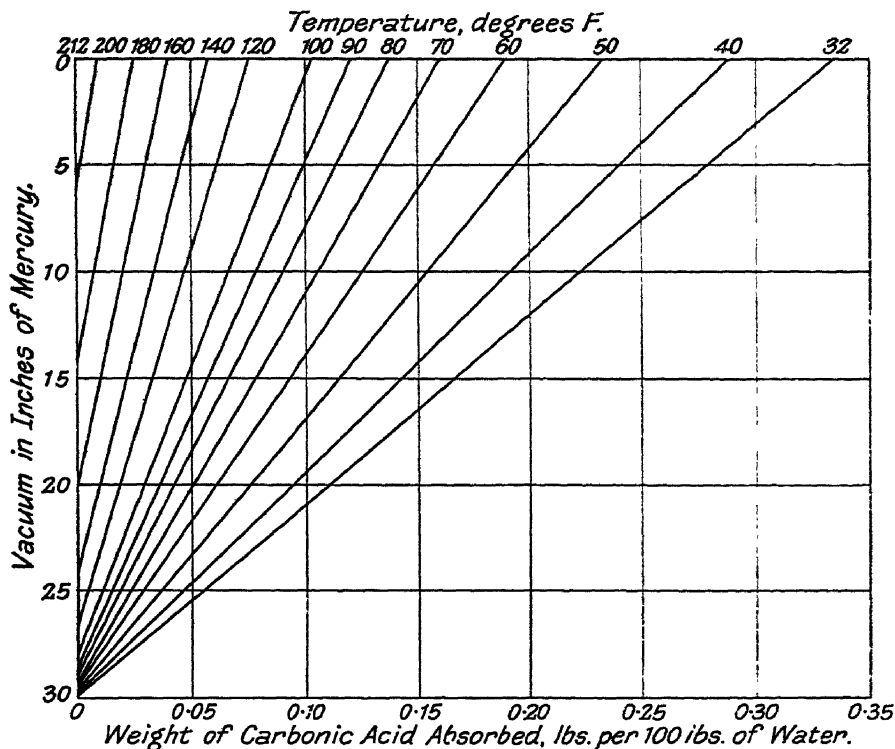


FIG. 37.—WEIGHT OF CARBONIC ACID ABSORBED, AT VARIOUS VACUA.

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course of his researches that oxygen alone had very little effect upon iron. All ordinary natural water, however, contains appreciable quantities of both oxygen and carbon dioxide, and even though the feed-water has been purified from the mineral salts, held in solution, it is now realized that the presence of these two gases together are all that is necessary to start corrosion. The conclusion arrived at from the exhaustive researches of the late Mr. James Weir was : " That when the feed-water contained both these gases in solution, the

iron oxide formed, due to the presence of the oxygen, reacted with the carbon dioxide, forming ferrous carbonate. This is dissolved in the water and reduced by the oxygen in it to iron oxide, while the carbon dioxide is liberated and is free to attack more iron oxide. Thus the carbon dioxide, no matter how small the quantity originally present, remains constant in amount and becomes a permanent agent in the reactions."

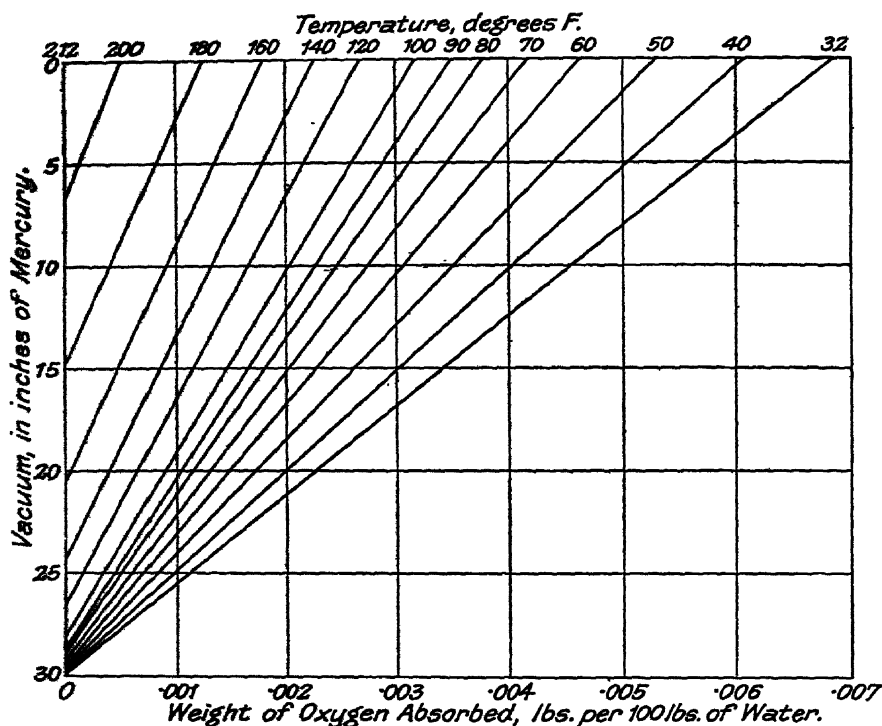


FIG. 38.—OXYGEN ABSORBED AT VARIOUS VACUA.

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Figs. 37 and 38 show the absorption of these gases in water from air for various temperatures and absolute pressures. It will be noted that the amount of each gas absorbed at a given temperature increases with the pressure, the increase being directly proportional to the pressure rise; also, that at any given vacuum the power of the water to hold each gas rapidly diminishes as the temperature rises. Of the various methods of feed-water treatment, that of distillation removes practically all the impurities including most of the dissolved oxygen, and the distilled water produced by evaporators is as free as

it possibly could be from scale forming and priming substances. For this reason, evaporators are to be preferred for the production of make-up feed-water in large power stations. Corrosion, however, is not prevented by an evaporator, and if an efficient service of pure gas-free feed-water is to be obtained, a form of de-aerating apparatus is necessary, preferably in conjunction with a closed feed system. One method of de-aerating feed-water consists of passing the feed-water on its way to the boiler through a chamber containing a large quantity of finely divided iron. This method, however, only removes the oxygen, leaving the carbon dioxide still in the water and if other gases are present, then under boiler conditions corrosion will still result. Another and very efficient method of de-aerating the feed-water consists of bringing the water to the boiling point under the particular conditions of temperature or pressure. This object may be attained by: (a) keeping the pressure constant and raising the temperature until a temperature corresponding to the pressure is obtained; or (b) by keeping the water temperature constant and lowering the pressure till the pressure corresponding to the fixed temperature is attained; or (c) by a combination of the above two methods. The most common method of de-aeration is that under heading (c), i.e. by simultaneously lowering the pressure and raising the temperature, thus de-aeration and feed heating can be carried out in the one piece of apparatus. A section of a Weir de-aerator and direct contact feed-water heater is shown in Fig. 39. The diagram is practically self-explanatory. From the foregoing remarks on the subject of boiler feed-water, it is seen that the ideal to be aimed at is a chemically pure water free from dissolved gases in general and carbon dioxide and oxygen in particular.

Routine Tests. The nature of the control tests for regulating the quality of the feed-water will depend upon the method by which the softened water is produced. Where softening is effected by chemical means as, for instance, in a lime and soda process plant, the treatment should be carefully controlled by testing the water entering and leaving the softening plant at least once every twenty-four hours, and in large power stations, or where the composition of the crude water is liable to frequent changes, tests should be made once or twice in each eight-hour shift. When taking samples of water for routine testing or analysis, care must be taken that the containing vessels are scrupulously clean and that the material

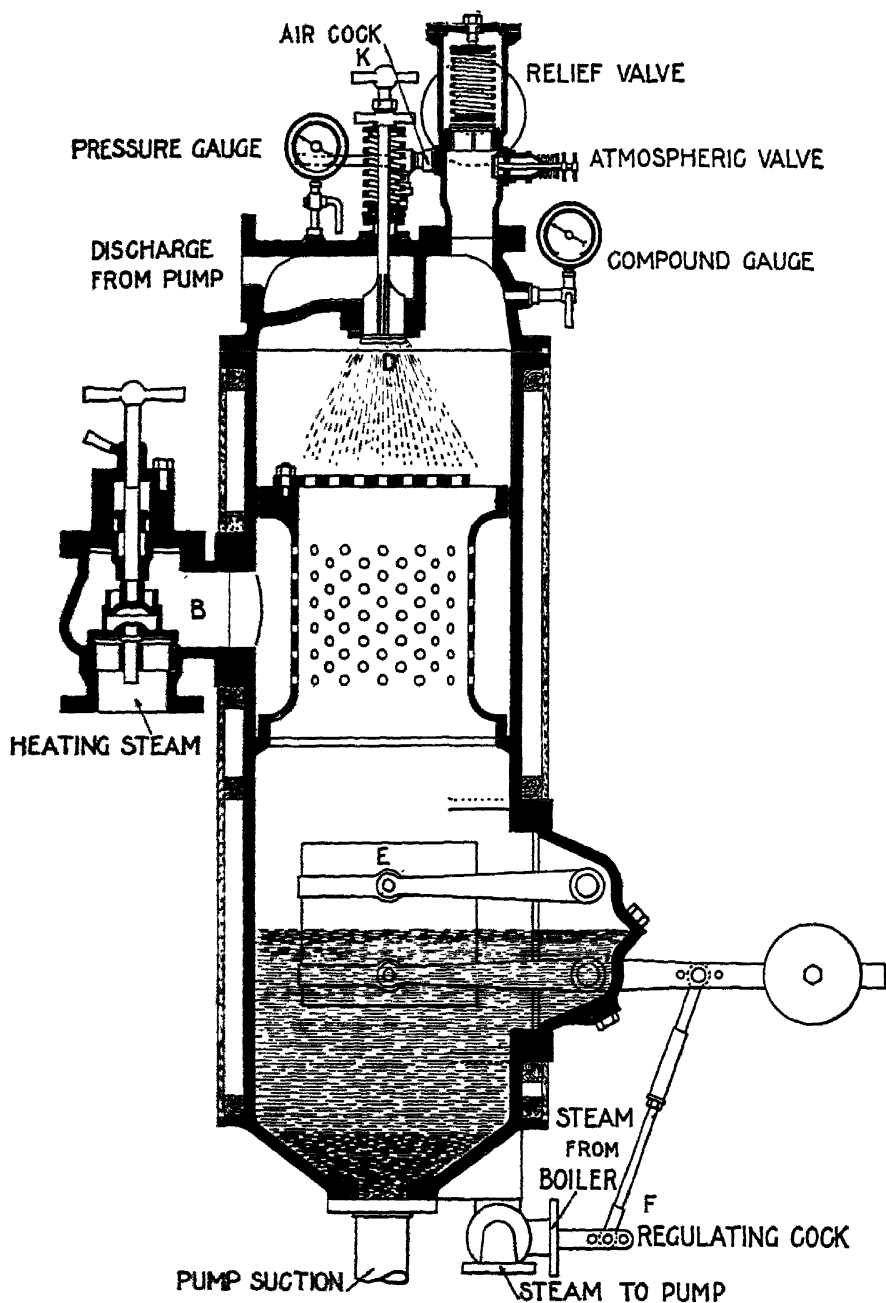


FIG. 39.—WEIR DIRECT CONTACT FEED-WATER HEATER AND AUTOMATIC REGULATING GEAR.

TABLE XV

ANALYSIS OF SAMPLES OF RIVER CLYDE WATER AT DALMARNOCK POWER STATION

	(a)	(b)	(c)
Calcium Carbonate	6.04 grains per gall.	8.0 grains per gall.	4.14 grains per gall.
Magnesium Carbonate	0.30 " " "	1.14 " " "	0.51 " " "
Calcium Sulphate	1.79 " " "	" " "	0.25 " " "
Magnesium Sulphate	2.82 " " "	3.49 " " "	1.83 " " "
Magnesium Chloride	0.35 " " "	" " "	" " "
Sodium Chloride	1.30 " " "	0.89 " " "	0.57 " " "
Sodium Sulphate	" " "	0.56 " " "	" " "
Iron, Alumina, etc.	0.25 " " "	1.68 " " "	0.07 " " "
Silica	0.47 " " "	0.39 " " "	0.38 " " "
Totals	13.32 " " "	16.15 " " "	7.75 " " "
Hardness by Wanklyn's Soap Solution	12.5°	15.25°	7.35°

Average charges of reagent according to state of crude water---

0.61 to 0.78 lbs., 90% lime, per 1,000 gallons

0.60 to 0.70 lbs., 90% soda, per 1,000 gallons

from which they are made will not affect the sample. Winchester quart bottles make very suitable containers if the precaution is taken to rinse them out thoroughly with some of the water from which the sample for testing is to be taken. The charges of lime and soda ash necessary to soften a given quantity of water can only be accurately determined from a complete analysis of the crude water. This method is the most accurate that can be devised, but as it is slow and complicated it is not practicable where a water is in daily use, and certain tests which will show in a few minutes, the hardness, alkalinity or acidity of the water and the strength of the reagents being used have been devised. These tests are quite simple and can easily be made by anyone provided sufficient care is taken in carrying them out. The following results of analyses (Table XV) show the effect of seasonal and climatic changes on the constituents of a river water, and the average amount of reagent necessary to soften 1,000 gallons of crude water. In practice, of course, these amounts are increased or decreased slightly, depending upon the state of the river as determined by the hardness and alkalinity tests.

There are various methods for the determination of the hardness of a water, but the soap test is the most useful and convenient, and if carefully carried out will give results of sufficient accuracy for the control of the reagents for the softening treatment. The soap test is based upon the fact that calcium and magnesium salts in solution will destroy or neutralize a quantity of soap roughly proportional to that of the salts. The standard soap solution used to titrate the water sample may be either Clark's or Wanklyn's. The fault in the soap test is that it does not discriminate with any degree of accuracy between the calcium and magnesium. The apparatus necessary for carrying out this test for hardness and for the alkalinity determinations is—

- 1 burette stand.
 - 2 50-c.c. burettes graduated in 1/10 c.c.
 - 1 100-c.c. glass-stoppered shaking bottle.
 - 2 5-in. diameter white porcelain evaporating dishes.
 - 1 150-c.c. graduated measuring cylinder.
 - 2 glass stirring rods.
 - 1 Winchester quart of Wanklyn's soap solution.
 - 1 Winchester quart N/50 sulphuric acid.
 - 1 pint of methyl-orange.
 - 1 pint of phenolphthalein.
- Supply of pure distilled water.

All these are shown in Fig. 40.

Before commencing the tests the pieces of apparatus to be used are thoroughly washed with the distilled water, and the burettes filled to the zero mark at the top of the scale. One burette contains the soap solution and the other the N. 50 sulphuric acid.

For the hardness test 70 c.c. of the sample are measured out and transferred to the shaking bottle. This quantity, 70 c.c.,

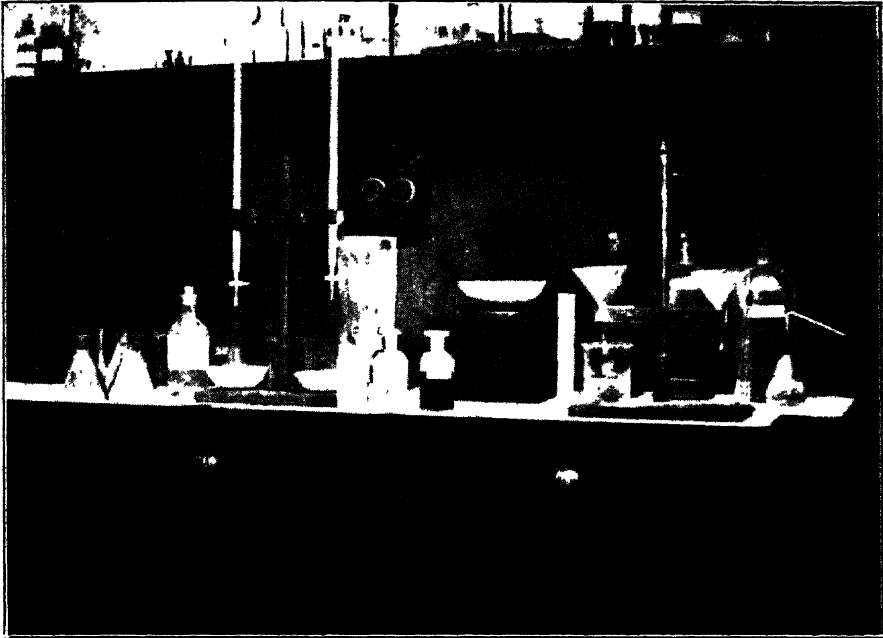


FIG. 40.—WATER-TESTING APPARATUS.

is such that it contains just as many milligrams as a gallon contains grains. It thus represents a miniature gallon. The soap solution is run from the burette into the shaking bottle 0.5 c.c. at a time, stoppering and shaking the bottle after each addition. A slight lather may form at first, but the bubbles will quickly break and disappear with a sharp hissing sound. More solution is added and the stoppering and shaking continued until a permanent lather about a quarter-of-an-inch thick is obtained, and which must remain unbroken, though possibly decreased in amount, for at least five minutes with the bottle lying on its side. If much magnesium is present in the water being tested a false lather may be obtained before the true lather is reached. This false lather can be detected

by uncorking the bottle and listening to the breaking of the bubbles ; if more soap is required these will be breaking quickly with a hissing noise. As more soap is added the sound becomes muffled, and near the end point of the titration there will be little or no sound at all. A few seconds should be allowed between shaking the bottle and listening to the sound. The number of cubic centimetres of soap solution required to produce the true lather, minus one, gives the hardness of the water in degrees ; 1° being equivalent to one grain per gallon of calcium carbonate. The deduction of 1 c.c. from the burette reading is necessary, because even distilled water requires a slight quantity of soap to make it lather. A water having a hardness of more than 15° should be diluted before testing, otherwise unreliable results will be obtained. In such a case 35 c.c. of the sample should be diluted with 35 c.c. of distilled water and the figure obtained multiplied by 2. A more accurate method of determining the hardness of a water, known as *Hehner's method*, gives much better results, since the operation is not affected to any extent by the presence of magnesium salts, and the values of both the temporary and permanent hardness can be accurately determined. Permanent hardness is due almost entirely to the sulphates of calcium and magnesium. The process is best carried out in a proper laboratory, but the addition of one or two standard solutions and indicators to the list of apparatus, previously mentioned, is all that is required. The necessary solutions are—

Decinormal sulphuric acid ($N/10 \text{ H}_2\text{SO}_4$).

1 c.c. $N/10 \text{ H}_2\text{SO}_4 = 0.005 \text{ gram CaCO}_3$.

Decinormal sodium carbonate solution. ($N/10 \text{ Na}_2\text{CO}_3$.)

1 c.c. $N/10 \text{ Na}_2\text{CO}_3 = 0.005 \text{ gram CaCO}_3$.

Methyl-orange is used as an indicator in the titrations, as it is not affected by carbonic acid. Briefly, the determinations are made as follows. The temporary hardness of the calcium and magnesium carbonates is first determined by titrating 500 c.c. of the sample with the $N/10 \text{ H}_2\text{SO}_4$. From the cubic centimetres of acid used the equivalent amount of CaCO_3 is calculated and expressed either as grains per gallon or parts per 100,000.

For the estimation of the permanent hardness 50 c.c. of the $N/10 \text{ Na}_2\text{CO}_3$ are added to 250 c.c. of the water, which is boiled for about half-an-hour. If magnesium salts are present the water is evaporated to dryness and the residue extracted

with water. The residue is next washed and filtered with boiled distilled water, and the cold filtrate made up to 250 c.c. ; 50 c.c. of the filtrate is taken and titrated with N/10 H_2SO_4 , using methyl-orange as an indicator. The permanent hardness can now be calculated from the number of cubic centimetres of acid used, and the total hardness obtained by adding together the temporary and permanent hardness. An example will illustrate the process more clearly—

ESTIMATION OF TEMPORARY HARDNESS

Water sample	500 c.c.
N/10 H_2SO_4 required in titration	7.3 c.c.
Equivalent CaCO_3 neutralized by 7.3 c.c. N/10 H_2SO_4	7.3×0.005 c.c.
	= 0.0365 gram.
Temporary hardness as parts of CaCO_3 per 100,000	
parts of water	200×0.0365
	= 7.3
Or, expressed as grains per gallon	7.3×0.7
	= 5.11

ESTIMATION OF PERMANENT HARDNESS

250 c.c. of water sample are boiled with 50 c.c. of Na_2CO_3 , filtered, and filtrate made up to 250 c.c.—	
Quantity taken for titration	50 c.c.
N/10 H_2SO_4 required in titration	8.8 c.c.
Permanent hardness in 50 c.c. taken	$10 - 8.8^1$
	= 1.2 c.c.
Therefore N/10 Na_2CO_3 corresponding to permanent hardness in the 250 c.c. of water	1.2×5
	= 6.0 c.c.
Permanent hardness as parts of CaCO_3 per 100,000	
parts of water	$6 \times 0.005 \times 400$
	= 12
Or, expressed as grains per gallon	8.4
Therefore, total hardness, parts per 100,000	19.3
And total hardness, grains per gallon	13.51

The alkalinity of the crude or untreated water can be determined, as described, for the estimation of the temporary hardness, and the treated or softened water is then tested as follows. The hardness is first estimated by titration with the soap solution as already described. For the estimation of alkalinity 70 c.c. of the sample are measured into a white porcelain dish and titrated with N/50 H_2SO_4 , using phenolphthalein as an indicator. This indicator is normally colourless, but changes to a purple pink tint in the presence of the

¹ 10 c.c. N/10 Na_2CO_3 were present in every 50 c.c. of the solution.

hydrates and carbonates of lime, magnesia, and soda, the colour being readily destroyed by the addition of an excess of acid. The acid required to destroy the colour indicates the alkalinity to phenolphthalein. A few drops of methyl-orange are then added to the sample and the titration continued until the least change from yellow to pink occurs. This represents the end point of the titration. The $N/50$ H_2SO_4 required for both titrations equals the total alkalinity expressed equivalent to grains per gallon of $CaCO_3$. The first part of the titration should be carried through with extra great care, and the point of the burette immersed in the sample. The colour change, when using methyl-orange as the indicator, can be more readily detected if 70 c.c. of the sample are also measured into another white porcelain dish and the same amount of methyl-orange put in as is used in titrating the sample. By comparing the colours of the sample and the blank the least change is easily noticed.

These tests of the treated water furnish the information necessary for the regulation of the lime and soda softening reagents. In a correctly treated water the alkalinity to phenolphthalein should be slightly more than half the total alkalinity, and the total alkalinity should be slightly more than the hardness. Generally speaking, if the alkalinity to phenolphthalein is greater by more than 0.5 c.c., it is desirable that the lime be reduced and, if the total alkalinity is greater than the hardness by more than 0.5 c.c., the proportion of soda ash requires decreasing. The following is an example of the figures obtained by testing, as described, a correctly treated water—

Crude Water—

Hardness	.	.	.	.	.	.	9.5°
Alkalinity	.	.	.	.	.	.	7.0°

Softened Water—

Hardness	.	.	.	.	.	.	3.7°
Alkalinity to phenolphthalein	.	.	.	.	.	.	2.6°
„ „ methyl-orange	.	.	.	.	.	.	2.1°

It is important that the water in the feed system be tested for the presence of corrosive gases in solution. Laboratory methods for the estimation of these gases are long and tedious and require a high degree of skill for accurate determination, but an instrument invented by the late Mr. James Weir enables the feed-water at any point of the system to be easily

and rapidly examined for corrosive properties. In this instrument, Fig. 41, the water to be examined is passed over one side of a polished steel disc or plate, which is heated on the other side by steam. If corrosive gases are held in solution

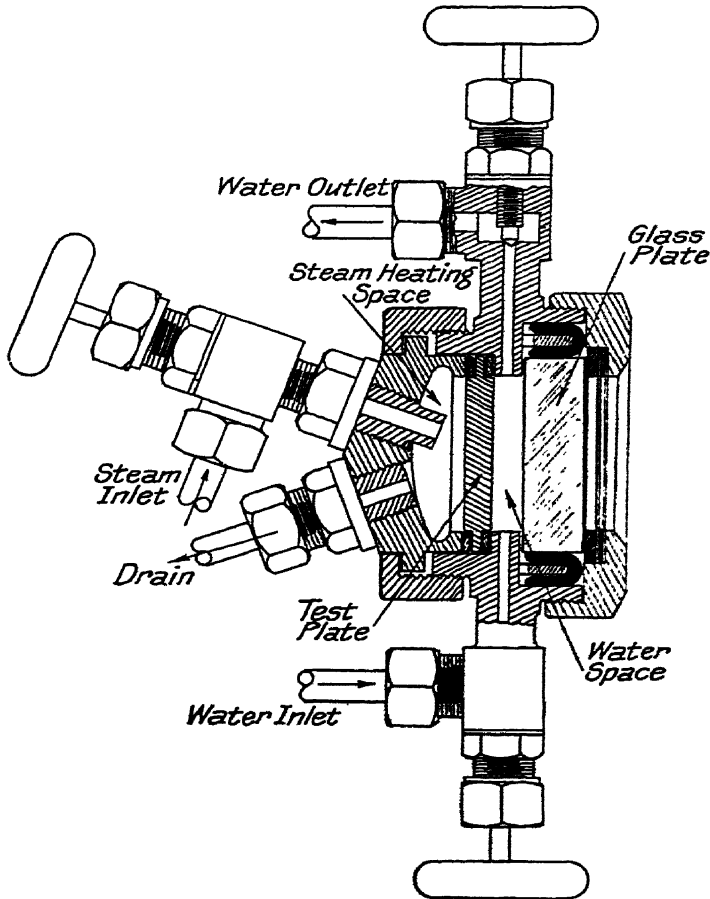


FIG. 41.—WEIR CORROSION DETECTOR.

by the water, these are released in an active chemical condition and their corrosive effect results in the discolouration of the polished surface of the disc. The instrument is easily transported and can be connected to the feed system at any point, or it may be permanently connected in any readily observable position.

Another source from which impurities may enter the feed

system is by way of condenser leakage. It is practically impossible to entirely prevent this leakage, and on the large units now installed, if the necessary attention is not given to condenser tube plates, etc., this leakage may reach appreciable proportions and seriously affect the whole feed-water system.

If the circulating water contains an appreciable amount of chlorides, regular testing, by the silver nitrate method, of both circulating water and condensate should be carried out, and from the information obtained from these tests, and a knowledge of the ratio of the circulating water to steam condensed, the percentage leakage may be calculated. In the silver nitrate test the chlorides are estimated volumetrically as chlorine, using potassium chromate as the indicator of the end point of the titrations. The silver nitrate solution can be prepared by dissolving 4.794 grams of pure AgNO_3 in a little distilled water and diluting to one litre; 1 c.c. of this solution equals 0.001 gram chlorine. The method of procedure is similar to the titrations already described; 70 c.c. of the sample are measured into a white porcelain dish and a drop of the indicator added. The AgNO_3 solution is then run in from a graduated burette until the slightest permanent brown tint is obtained. The number of cubic centimetres of AgNO_3 solution used, less 0.05 c.c., equals the chlorine in the sample expressed as grains per gallon. Where the silver nitrate test is not applicable, an electrical method of determining condenser leakage can be used. This method consists of the estimation of either the resistance or conductivity of equal volumes of circulating water and condensate, measured at a standard temperature. Suitable test apparatus for this purpose is shown in Fig. 42.

Tests should also be made frequently on the water in each boiler. There is at present no hard and fast rule as to when a boiler should be blown down. In many cases boilers are blown down far too frequently, but on the other hand, of course, there are many instances in which the reverse is the case. If the make-up water is carefully treated, and if the percentage of make-up water to total water evaporated does not exceed about 5 per cent, it will be sufficient if the steaming boilers are blown down from one to two inches once in twenty-four hours. Blowing down should be carried out shortly after the boiler has been taken off the range, as the impurities are then in an easily removable condition, and the maximum concentration will be in the lower parts of the boiler and in

the vicinity of the blow-down connection. One method of determining how long a boiler should steam without blowing down is by taking, say, three periods: twenty-four hours, forty-eight hours, and seventy-two hours. At the end of each of these periods the boiler is blown down and a sample of the blown-down water taken for analysis. The sodium, scale forming, and other salts are then estimated, and from a knowledge of the total evaporation of the boiler for the various

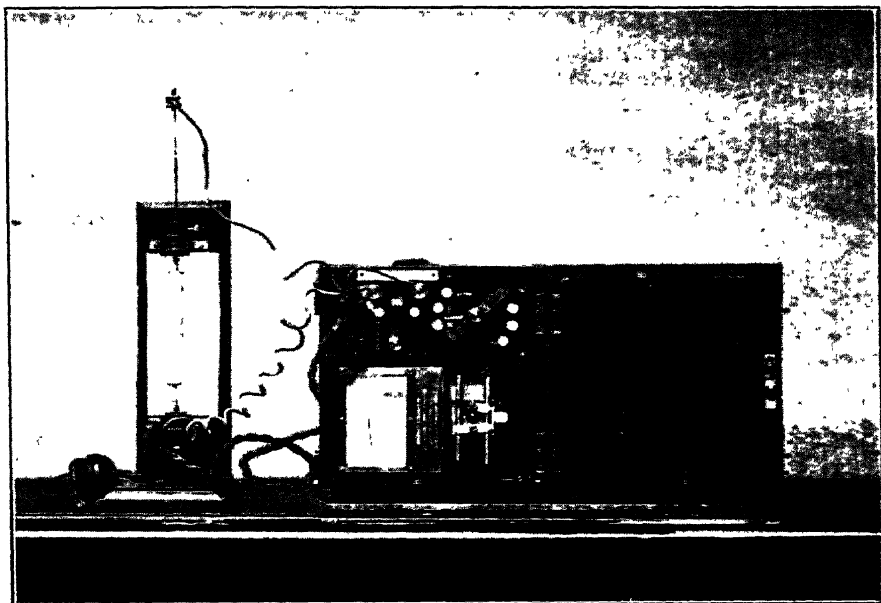


FIG. 42.—DIONIC TEST APPARATUS.

periods, the rate of concentration of the various salts is arrived at. It then remains to fix a definite degree of concentration, corresponding to a definite amount of water evaporated at which blowing down should take place. When a boiler is taken out of commission for cleaning purposes, samples of scale from the bottom tubes and deposit from the main drum or other points should be taken for analysis, as much useful information can often be obtained from this source. The following are analyses of scales from different boilers, the crude make-up feed-water was drawn from the same source in each case, and softened by lime and soda process plants before being fed to the boilers. In the case of (a), however, no attempt was made to regulate the charges of lime and

soda to suit the varying nature of the crude water, with the result that the water being fed to the boilers was worse than before treatment.

(a)

ANALYSIS OF SAMPLE OF SCALE FROM BOTTOM TUBES OF SMALL
B. & W. BOILER

Silica	14.03%
Oxide of iron, alumina, etc.	3.69%
Sulphate of lime	51.07%
Carbonate of lime	12.50%
Oxide of lime	11.74%
Oxide of magnesia	2.47%
Organic matter, etc.	4.50%

The above scale was very hard, of a porcelain like nature, and difficult to remove.

(b)

ANALYSIS OF SAMPLE OF SCALE FROM FIRE-ROW OF TUBES OF LARGE
B. & W.C.T.M. BOILER-FED WITH CORRECTLY-TREATED
MAKE-UP FEED-WATER

Calcium sulphate	4.760%
Calcium carbonate	60.785%
Magnesium oxide	7.520%
Silicates	15.050%
Ferrous salts, etc.	7.010%
Combined water, etc.	4.875%

A sample of the deposit from the main drum of the same boiler was also taken. This deposit was of a light floury nature, very easily removed, and gave the following values on analysis—

Calcium sulphate	1.75%
Calcium carbonate	4.07%
Magnesium oxide	22.14%
Silicates	22.45%
Ferrous salts, etc.	47.02%
Undetermined	2.57%

The loss in efficiency due to scale is difficult to determine, as this loss depends greatly on the nature of the scale. Generally speaking, a soft porous scale will have less effect on the heat transmission rate than a hard scale. There is only one method of preventing scale forming in a boiler, and that is by feeding only pure distilled or correctly treated water. Various claims are made by the manufacturers of boiler compounds as to the effectiveness of their products in preventing scale, but the majority of these compounds are

only quack remedies. There are certain paints, however, which applied to the inner surfaces of the boiler do prevent the adhesion of scale and deposit, and are useful in that cleaning is greatly facilitated, tube cleaning being possible by the usual wire-brush instead of by the longer and more expensive method of turbinizing. Of these paints "Alkala" and "Apexior" have been found to give very good results. Before applying either of these paints to the boiler plates the surfaces must be thoroughly cleaned and wire-brushed.

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CHAPTER VII

TURBINE-ROOM EFFICIENCY

General. Broadly speaking, there are two distinctive types of turbines employed in modern power station work, these are : (1) the impulse machine as represented by the Rateau, Zoelly, and Curtis ; (2) the impulse-reaction, or commonly termed reaction machine, as represented by the Parsons and Ljungström turbines (Figs. 43 and 44).

There are, of course, other types of turbines employed in power stations. These, however, are mostly hybrid machines, being combinations of the types previously mentioned. An example of a combination turbine is that commonly referred to as the disc and drum type. In the older type of Parsons turbine the weak spot was at the blade tips of the high pressure section. The replacement of this section by a velocity wheel eliminated tip leakage and confined the high pressure and temperature to the first set of nozzles. This combination of velocity wheel and reaction stages was termed a disc and drum turbine.

Turbine-room heat balance can be affected by the inherent weaknesses peculiar to each type of turbine, but providing that the plant is competently operated there is very little to choose between the two distinctive types, the old trouble with the high pressure end of the reaction turbine being now overcome by the use of end tightened blading and the employment of fine axial clearances. The various losses common to both types of turbine can, if allowed to become excessive, affect the heat balance to a great extent, in the form of increased steam consumption, and if these losses are to be kept at a minimum the plant must be competently operated and kept in a high state of maintenance.

The general trend in turbine design is to work with the highest possible pressure and superheat and to keep the condenser back pressure to the lowest value practicable. The great waste of heat rejected to the circulating water cannot be avoided, and all that the operating engineer can do at the low pressure end is to work his plant at the most economical absolute pressure (which is not necessarily the lowest).

It is in this trend towards higher pressures and temperatures

that it is claimed the impulse turbine has advantages over the reaction machine, as generally the only portions of the turbine frame, subjected to the full steam pressure and temperature, are the governing valves and chest and the first stage nozzles. It is claimed, however, that the reaction type of turbine will maintain its original efficiency over a longer period of time than turbines of the impulse type.

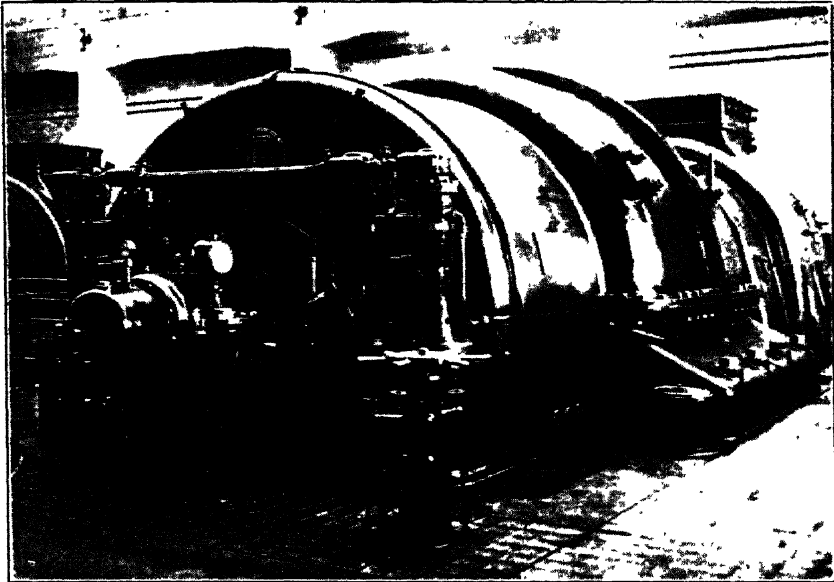


FIG. 43.—FRASER AND CHALMERS'S IMPULSE TURBINE.

It is well understood that the efficiency in steam-using equipment depends almost entirely on design and is not greatly influenced by operation. The water rate or steam consumption of an engine or turbine depends on the suitability of the apparatus, i.e. its design, for a given pressure, temperature, and vacuum, and as long as the steam conditions are correct, and the machine kept as near to mechanical perfection as possible, it will operate at its maximum designed efficiency. This being so, the engineer-in-charge must endeavour at all times to keep the initial and final conditions as near to the specified conditions as possible. The initial conditions, which are the boiler, or rather stop-valve pressure and temperature, are practically constant for all the sets in one station, and as the pressure gauges are usually easily observable from any

point on the steam side of the turbine-room, variations should be instantly detected and corrected. On the other hand, the terminal conditions, i.e. the absolute pressure carried in the condenser, condensate and circulating water temperatures, etc., are only constant for each particular machine and load : points very often overlooked. The importance of the terminal conditions is emphasized later.

Variations in Initial and Final Conditions. Variations in the initial and final conditions of the steam flowing through the turbine affect the steam consumption for the following reasons. The available heat drop per pound of steam flowing, is a function of the initial pressure, initial temperature, and final absolute pressure or vacuum. Any variation in either or all of these independent variables changes the value of the available heat drop. Further, any turbine designed for given specific initial or final conditions will possess certain efficiency characteristics over a given range of initial pressure, initial temperature, and final absolute pressure. The change in efficiency is due to an altered heat distribution throughout the turbine stages, which being originally designed for certain values, utilizes the new heat drop with either increased or decreased losses. The final change in consumption is a combination of the change in available heat drop and the change in the efficiency characteristic.

To take the case of changes in the initial pressure. It will be seen by reference to a heat-entropy diagram that with a constant value of initial temperature and absolute pressure, any increase or decrease in steam pressure from the initial state point of the steam, will result in an increase or decrease of the available heat drop, and with a turbine possessing a constant efficiency over the range of initial pressure variations chosen, the steam consumption will vary in direct proportion to the available heat drop. For every initial pressure other than its designed initial pressure, a commercial turbine possesses a definite efficiency which is different from that at the designed pressure. The final effect of any change of initial pressure on the steam consumption is, therefore, a combination of the variations in available heat drop and efficiency. Any variation in initial temperature or final absolute pressure also results in a change to the steam consumption, which is also a combination of the available heat drop and efficiency caused by the altered conditions. As in practice the field of variation is generally limited, it is usual to treat the variations in steam



FIG. 44.—PARSONS REACTION TURBINES, CARVILLE POWER STATION.

consumption as a factor or percentage of that at the designed conditions. By adopting this percentage or factor method, simultaneous variations of initial pressure, initial temperature, and final absolute pressure can be simply treated. It resolves itself into the algebraic addition or multiplication of the correction factors usually supplied by the designers of the turbine.

It will be found on investigation that considerable variation exists in the values of these factors for similar given conditions,

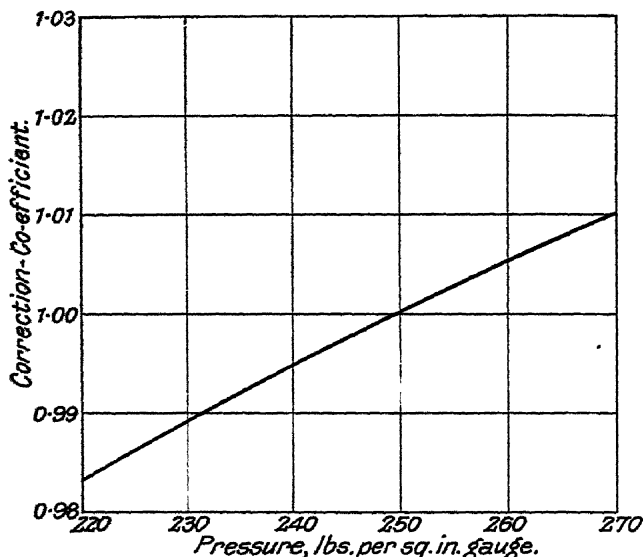


FIG. 45.—PRESSURE CORRECTION CURVE FOR
18,750 KW. TURBINE.

Specified conditions—

Pressure, 250 lbs. per sq. in. gauge.
Total temperature, 650° F.

Vacuum, 29.1 ins. Hg.
Barometer, 30.0 ins. Hg.

and no broad rule can be laid down to embrace all cases. The factors are influenced by individual design, specific initial conditions, output, etc., and stress must be laid on the engineer-in-charge obtaining the correct factors for the plant under his care and the checking of the values of these factors against results obtained in actual practice for the plant in question. In Fig. 45, 46, and 47 are shown the correction curves for the initial and terminal conditions of one particular design of turbine, and though these curves will be more fully dealt with later in connection with the correction of test figures to standard conditions, reference to them at this point will help to make clear the effect of allowing the steam pressure,

steam temperature, or condenser absolute pressure to vary from the specified values.

Initial Pressure Variations. Referring first of all to Fig. 45, the curve shows the effect of variations of the initial pressure, the abscissae being the range of pressures dealt with and the ordinates the values of the correction factor, by which the steam

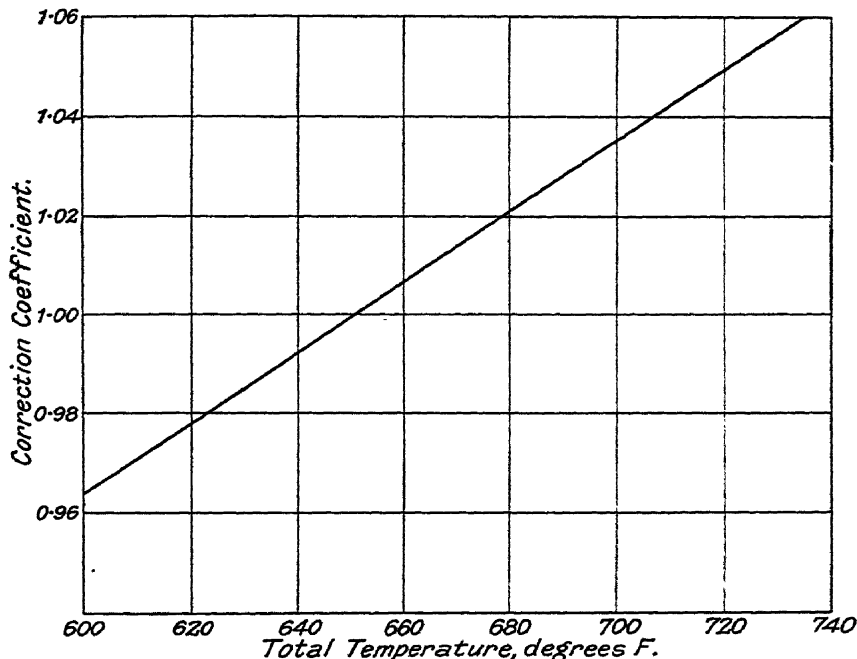


FIG. 46.—SUPERHEAT CORRECTION CURVE FOR
18,750 KW. TURBINE.

Specification conditions—
Pressure, 250 lbs. per sq. in. gauge.
Total temperature, 650° F.

Vacuum, 29.1 ins. Hg.
Barometer, 30.0 ins. Hg.

consumption at any particular pressure will have to be multiplied to correct it to standard conditions, in this case 250 lbs. per sq. in. It will be noticed that the correction factor at the specified pressure is unity, therefore the application of the correction factors resolves itself into the addition or subtraction of percentages. To show the effect of allowing the initial steam pressure to fall below the specified value, assume that with a given load on the turbine, and, for the sake of simplicity, that the other conditions remain constant, the steam consumption is 10.50 lbs. per kilowatt-hour. If the steam pressure for some reason or other fell to 230 lbs. per sq. in. the consumption

would increase to 10.616 lbs. per kilowatt-hour, the correction coefficient being read from the point at which the curve intersects the 230 lbs. per sq. in. pressure line. Such a fall of pressure as is given in the preceding example is, of course, unthinkable in a modern power station, except under abnormal conditions.

Initial Temperature Variations. The effect of allowing the total temperature of the steam to fall from the specified value can be illustrated by reference to Fig. 46. The specified temperature is 650° F. and, assuming the steam consumption to be 10.50 lbs. per kilowatt-hour for a given load, then a fall in temperature to 600° F., other conditions remaining constant, would result in the steam consumption increasing to 10.892 lbs. per kilowatt-hour. In a well-operated station variations in the value of the total steam temperature will be in the region of only about 10° F. from the specified conditions, but in many instances variations as great as that given in the example are everyday occurrences, and in some cases the total temperature is continually a considerable amount below the specified value: inefficient boiler house operation being principally responsible for this state of affairs. So far, only variations in the initial conditions have been dealt with, but their effect on the steam consumption under daily operating conditions is almost negligible by comparison to the effect produced by variations in vacuum. The word vacuum is really an erroneous term and has no meaning unless accompanied by the corresponding height of the barometer, and in dealing with turbine terminal conditions or condenser questions the engineer ought to train himself to think and speak in terms of absolute pressure.

Absolute Pressure Variations. The question at what value the absolute pressure for any turbine should be maintained can only be answered from carefully tabulated results, covering the range of loads carried by the turbine. No definite rule can be laid down to cover all types of turbines, as the most economic values of absolute pressure for any particular turbine will vary with the loads, and are governed by the design of the low pressure stages. Generally speaking, the lower the absolute pressure maintained in the condenser, the lower will be the steam consumption of the turbine per kilowatt-hour, but the fact must not be lost sight of, that lowering the absolute pressure decreases the temperature of the condensate, and a point is reached where the gain due to the decreased absolute

pressure is offset by the loss of heat in the condensate and the extra power taken by the condenser auxiliaries, the net result being an increase in overall thermal expenditure. The effect on the steam consumption of variations in absolute pressure

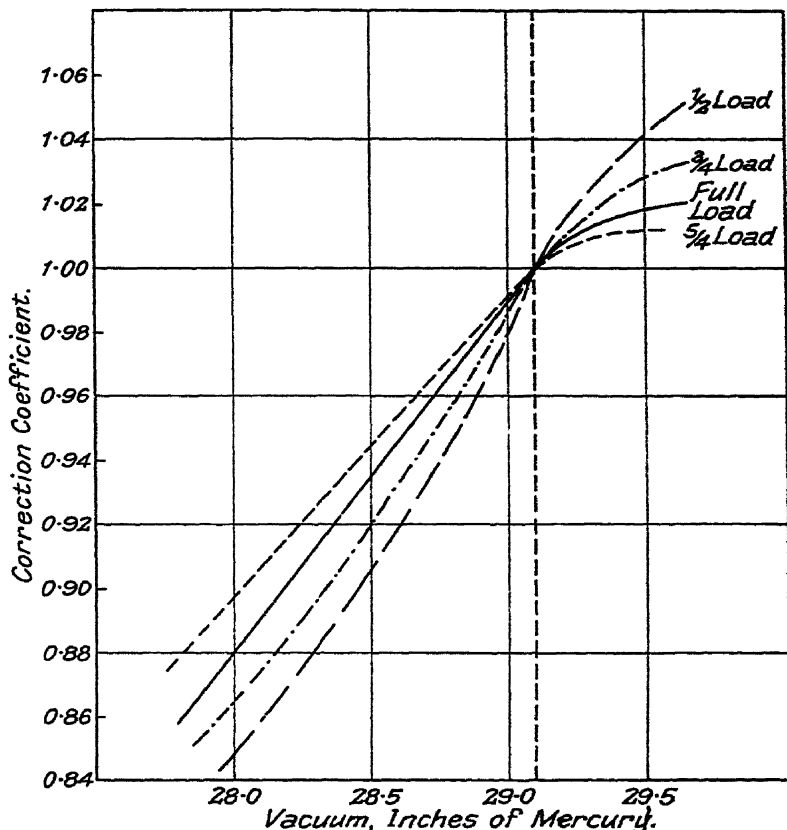


FIG. 47.—VACUUM CORRECTION CURVES FOR
18,750 KW. TURBINE.

Specified conditions—
Pressure, 250 lbs. sq. in. gauge.
Total temperature, 650° F.

Vacuum, 29.1 ins. Hg.
Barometer, 30.0 ins. Hg.

for one particular design of turbine can be followed by reference to Fig. 47. The abscissae represent the range of variations, and the ordinates are the correction factors as before. Assume that with full load on the turbine the steam consumption is 10.50 lbs. per kilowatt-hour, and the value of the absolute pressure is 0.9 ins. of mercury (i.e. 29.10 ins. of vacuum by mercury column with the barometer at 30.00 ins. of mercury).

Further, assume that the absolute pressure rose to 2.0 ins. of mercury (or under the barometric conditions stated 28.00 ins. vacuum by mercury column), due to inefficient operation, then the steam consumption will increase to 11.931 lbs. per kilowatt-hour. In reality the effect would be worse and the results complicated by the variation of the other factors.

All the foregoing emphasizes the necessity of the turbine plant being operated at the specified conditions, and stress is again laid on the necessity for engineers in charge of turbine plant obtaining the curves applicable to their own particular plant, and realizing the effect on the coal bill of operating the plant in their charge for any length of time at lower initial pressures and temperatures, and higher terminal absolute pressures than those specified.

Initial Pressure Measurements. For efficient turbine-room operation a sufficiency of instruments must be provided for the measurement of initial and terminal conditions. The number of instruments required will be governed by the type of turbine to which they are to be applied. Dealing first of all with pressure measurements it is desirable, if the turbines are of the impulse type, that pressure gauges should be connected to give the conditions before the governor valves, after each governor valve, and after the first expansion. If steam is bled from one or more stages of the turbine for feed-water heating, further pressure gauges should be installed to indicate the conditions at these points. Where reaction turbines are employed, pressure gauges should be connected to each section of the turbine. Pressure indications are a direct guide to the operating engineer as to the internal conditions of the turbine, and as will be shown later they also provide a means of almost equal accuracy to other instruments, of indicating the steam consumption. For a given set of conditions a certain pressure or pressures before the first nozzles of an impulse turbine, or pressure before the first expansion of a reaction turbine, a definite weight of steam will flow through the turbine. Further, for a given set of conditions, a close relation exists between the weight of steam flowing through the turbine and the load developed at the alternator terminals.

Consider a turbine with one governing valve by which the steam is throttled before passing to the first nozzles, then for every load carried by the turbine there will be a definite pressure at the inlet to the nozzles, and if readings of the pressure and

loads be plotted on squared paper, the points will be found to lie along an approximately straight line. If the relation between pressure and load varies at any future time it is a sure indication that something is wrong inside the turbine. Where a turbine is equipped with two or more governor valves controlling sets of nozzle arcs, complications arise in using the pressure indications after the governor valves for checking the condition of the turbine, but good results can be obtained in the case of impulse turbines by taking out a line showing the relation between load carried on the turbine and the corresponding pressure after the first expansion. It must be borne in mind that within certain limits a variation in the relation between pressures and loads may not always be due to internal deterioration of the turbine, these relations being affected to a certain extent by changes in the initial and final conditions of the steam.

Generally speaking, however, the line of loads and pressures may be depended upon as an infallible guide to the condition of the turbine. The line may be either based on the designer's figures or, preferably, plotted from observed readings with the turbine, new or in good condition. Where turbine plant is equipped with a Lea recorder or other indicating apparatus for the measurement of the condensate of each main unit, rate of flow per hour can be substituted for load values when determining the graphs. It is then an easy matter to check any given pressure against the indication of the rate of flow per hour. A graph such as has been described is shown in Fig. 48. It is a good plan to take these out for each turbine and, after framing, hang them in a prominent position on the wall at the steam end of the machine.

Pressure gauges, like other power station instruments, require a certain amount of attention and should be periodically checked by a dead-weight testing outfit. The correction scale can then be kept up to date, a copy being either attached to the gauge or fixed near it, so that when turbine tests are being carried out the corrections can be applied as the instrument is read.

Initial Temperature Measurements. In many power stations it will be found that the engineers in charge are not provided with any means of ascertaining the temperature of the steam supplied to the turbines. The necessity of maintaining the steam temperature at the specified value has already been enlarged upon, and unless provision is made in the form of

either thermometers or thermocouples, variations in the temperature of the steam cannot be readily detected. It is customary for manufacturers of turbine plant to provide all vital points with thermometer pockets. Where high temperature measurements are to be made, the necessity of having these pockets deep enough and filled to the correct level with mercury has already been referred to when discussing the

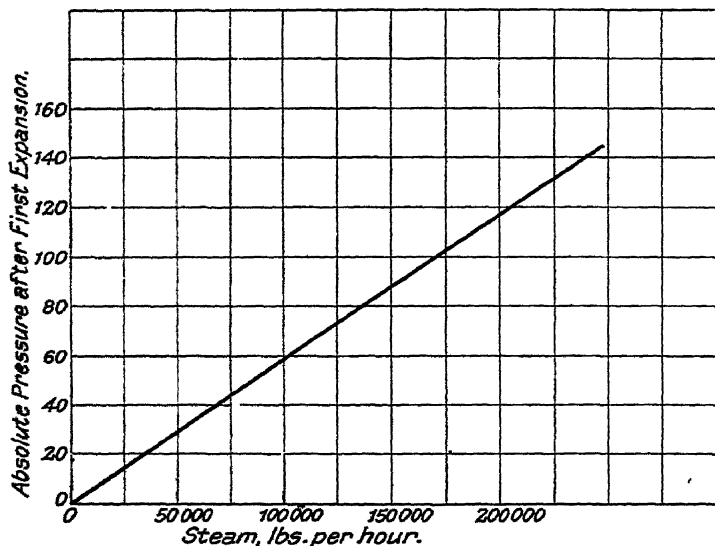


FIG. 48.

Relation between steam flow and first expansion absolute pressure—Conditions : 250 lbs. \square g., 650° F. steam temp., 0.9" Hg. absolute pressure.

measurement of high temperature steam in the boiler-rooms. It will not always be convenient to measure turbine initial steam temperature by means of thermometers except during tests, and where the pockets are beneath the floor level, it will be found advantageous to fit a thermocouple at the governor steam chest and mount the indicator on the wall, and here it ought to be mentioned that all the instruments for each turbine should, as far as possible, be grouped together and mounted on the turbine-room wall, opposite the steam end of the machine. Where the layout of the plant will not permit this, such as in cases where turbines are installed with their axes parallel to the length of the turbine-room, special instrument panels should be erected at each machine (Fig. 49).

Steam Consumption Measurements. Generally speaking, turbine steam consumption is the criterion of efficient turbine-room

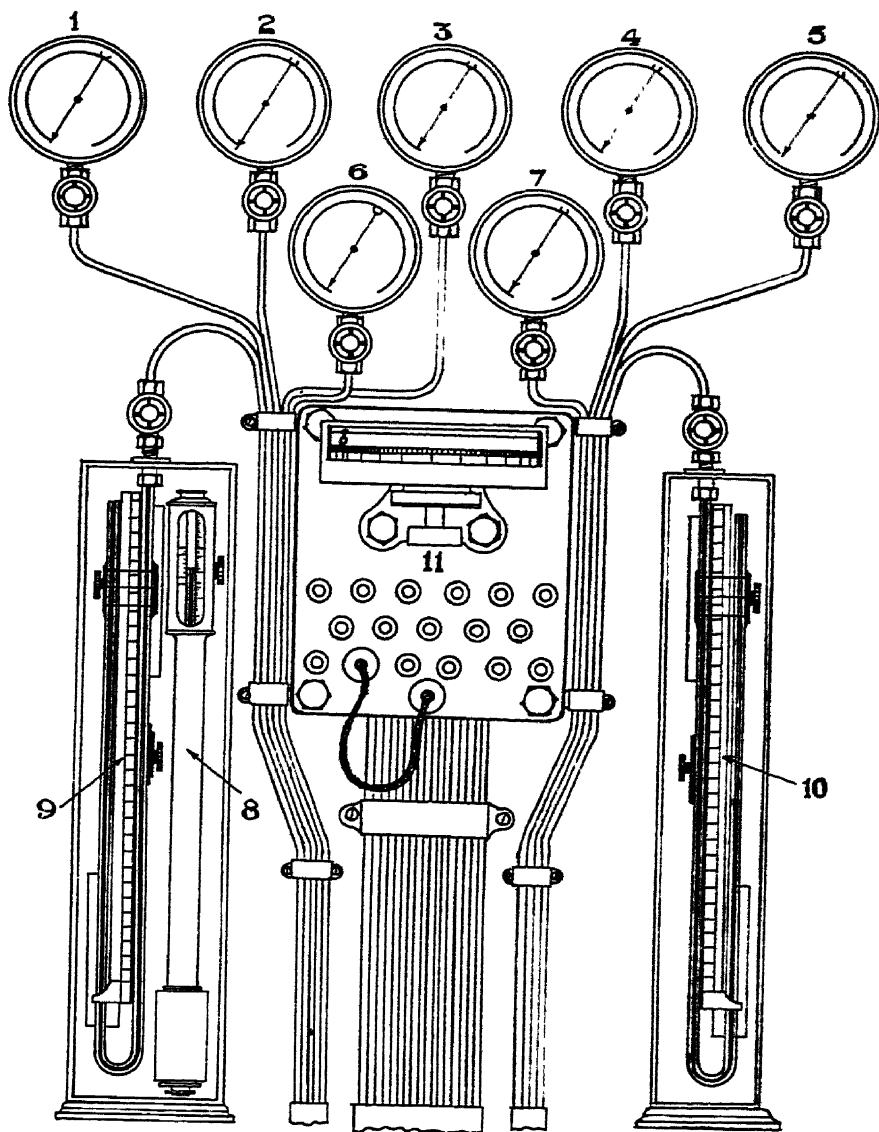


FIG. 49.—TURBINE INSTRUMENT PANEL.

- | | |
|---------------------------------------|--|
| 1. Stop valve pressure. | 7. Governor relay pressure. |
| 2. Pressure after 1st governor valve. | 8. Barometer. |
| 3. Pressure after 2nd governor valve. | 9. Vacuum at exhaust flange. |
| 4. Pressure after 3rd governor valve. | 10. Vacuum at bottom of condenser. |
| 5. Pressure after 1st expansion | 11. Thermocouple plug-board for all neces- |
| 6. Bearing oil pressure. | sary temperature readings. |

performance. In operation the principle factors governing the steam consumption are: steam conditions, condenser performance, alternator efficiency, load factor, and the mechanical condition of the unit. The engineer, therefore, must be fully familiar with the effect of these factors on the steam consumption of the plant in his charge.

Turbine steam consumption is the amount of steam expressed in lbs., taken by the turbine to produce one kilowatt-hour at the alternator terminals, or switchboard, as the case may be, and is often referred to as the water-rate of the turbine. This value must not be confused with the station water-rate, which includes make-up water.

The Kent Steam Meter. It is imperative if a turbine is to be efficiently operated that the steam flowing through the turbine for any period must be known. This can be accomplished by either measuring the weight of steam supplied to the turbine, or the weight of condensate discharged from the condenser, and a number of excellent appliances for either of these purposes are on the market. One of the best known instruments for metering the steam supplied to a turbine is the Kent steam meter. In operation this instrument indicates the rate of flow in lbs. per hour, gives a graphical record on a drum recorder of the rate of flow, and by an integrating mechanism the steam consumption for any period can be ascertained.

Condensate Measurement. In certain power stations, however, turbine consumption is determined from measurements made of the weight of condensate, and considering everything this method is preferable to that already mentioned. Apparatus for the measurement of turbine condensate can be constructed of a much more robust nature and without impairing the accuracy of the indications or records, than the delicate instruments necessary if measurements are made on the steam side.

The majority of instruments used for metering condensate are of the open type in which the water is made to flow from a tank over a weir of special shape.

Meters of the Venturi type are sometimes used, the Venturi tube forming part of the condensate piping system. The best known instruments of the first type, i.e. in which the water is measured from the rate of flow over a weir, are the Lea recorder, Precision water meter, and the Paterson fluxograph.

The "Lea" Recorder. The "Lea" recorder, Fig. 50, is so well known to station engineers that it hardly requires

description. When water is caused to flow over a V-shaped notch it can be measured very accurately. The measuring mechanism of the Lea recorder is actuated by a float in a tank containing a V-notch. The condensate from the turbine is passed through this tank and over the notch on its way to the hotwells or lift pumps.

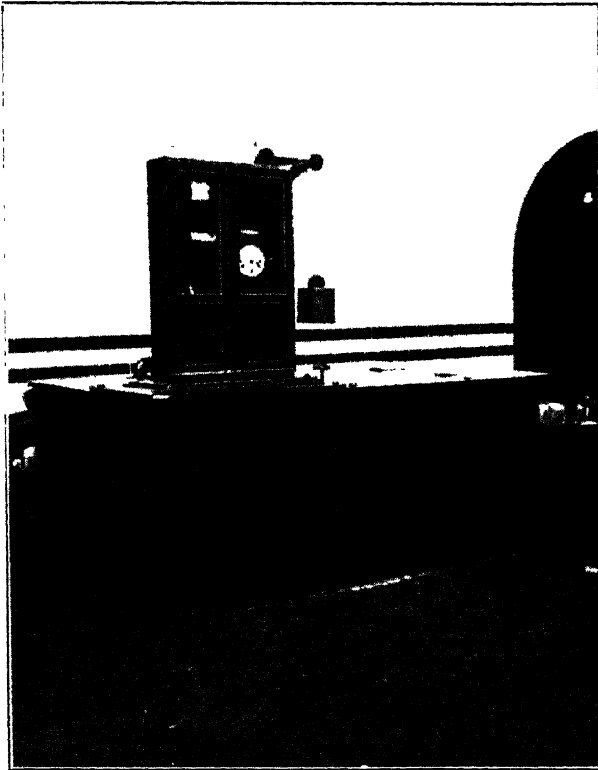


FIG. 50.—“LEA” RECORDER.

The instrument gives a graphical record of the steam consumption, a direct indication of the rate of flow at any instant, and integrating mechanism is actuated by a specially shaped toothed spiral drum, in a somewhat similar manner to the Lea coal meter previously described.

It is customary with meters of the V-notch or weir type to mount the indicating, recording, and integrating mechanism in a case on top of the float tank, but in case of lack of space, or for other reasons, the measuring tank can be erected in the

TABLE XVI
RATES OF FLOW THROUGH 90° "V" NOTCH

Depth in Notch in Inches.	Flow per Hour.		Depth in Notch in Inches.	Flow per Hour.	
	Gallons.	Lbs.		Gallons.	Lbs.
1 inch	114	1,140	9 inches	27,796	277,960
2 inches	648	6,480	10 "	36,174	361,740
3 "	1,783	17,830	11 "	45,903	459,030
4 "	3,661	36,610	12 "	56,872	568,720
5 "	6,394	63,940	13 "	69,471	694,710
6 "	10,086	100,860	14 "	83,611	836,110
7 "	14,829	148,290	15 "	99,351	993,510
8 "	20,706	207,060			

(Lea Recorder Co.)

Based on an average water temperature of 100° F. For cold water (temperature about 60° F.) add 1% to the above weights.
For very hot water (temperature above 180° F.) deduct 1% from the weights given in the table.

condenser basement and the float rod carried up to the case containing the mechanism on the turbine-room floor.

The table shown on p. 166 gives the rate of flow per hour through 90° V-notches, calculated at a temperature where 1 gallon of water equals 10 lbs. The values are deduced from Thomson's formula—

$$\text{Cubic feet per min.} = 0.305 H^2 \sqrt{H}$$

where H = depth in inches, i.e. from level of water to apex of notch.

For test purposes it is customary to desire a closer degree of accuracy in measuring turbine condensate than can be obtained in the types of apparatus described.

Venturi Tube Meters. The Venturi type of meter has been referred to in an earlier section of the book, and remark was made concerning the different uses to which small home-made Venturi tubes can be put, for the supply of data from which the plant performance can be approximately comparatively judged. It will therefore not be out of place at this point to consider broadly the principle upon which instruments of the Venturi type operate. A diagrammatic sketch, representing a Venturi tube in section is shown in Fig. 22 (page 82). The principle upon which Venturi tubes operate is known as "Bernoulli's Theorem" which may be stated as follows. If a constant quantity of water is flowing through a tube of varying diameters in a given time, with varying velocity due to the different diameters, then (excepting any loss due to friction), the total energy remains constant and the sum of the potential head, pressure head, and velocity head remains constant.

In the case of the Venturi tube shown in Fig. 22—

Let A = area in square feet of the cross section of the tube at entrance or up-stream section.

V = velocity of water in feet per second at the point A .

a = area in square feet at nozzle throat.

v = velocity of water in feet per second at the nozzle throat.

g = acceleration due to gravity = 32.16.

h = head corresponding to velocity V .

h_1 = head corresponding to velocity v .

Then $V^2 = 2gh$ and $v^2 = 2gh_1$.

$$v^2 - V^2 = 2gh_1 - 2gh = 2g(h_1 - h).$$

The value of $(h_1 - h)$ is the amount by which the velocity head at the throat is greater than the velocity head at the entrance. A differential gauge connected, as shown in Fig. 22, will indicate the reduction in pressure, and $(h_1 - h)$ may be written H , the foregoing equation now becoming—

$$v^2 - V^2 = 2gH.$$

It should be pointed out here that if the readings of the differential gauge are in inches of mercury, the value must be converted to equivalent feet of head of the fluid or other medium being measured. In the case of a mercury filled gauge measuring water flow the manometer readings would be multiplied by the constant 1.13.

The amount of water passing the point A is the same as that which passes through the throat, therefore—

$$\begin{aligned} VA &= va \\ V &= \frac{va}{A} \\ \text{or } V^2 &= \frac{v^2 a^2}{A^2} \end{aligned}$$

Substituting this value for V^2 in the previous equation, we get—

$$v^2 - \frac{v^2 a^2}{A^2} = 2gH$$

and the theoretical velocity in feet per second through the throat of the Venturi tube, assuming no loss due to friction, is—

$$v^2 = \frac{2gH}{1 - \frac{a^2}{A^2}} \text{ or } v = \frac{\sqrt{1}}{\sqrt{1 - \frac{a^2}{A^2}}} \times \sqrt{2gH}$$

If C is a constant representing the efficiency of the nozzle, the velocity in feet per second through the nozzle throat is—

$$v = C \frac{\sqrt{1}}{\sqrt{1 - \frac{a^2}{A^2}}} \times \sqrt{2gH}$$

For small home-made tubes, if these are carefully finished, C will have a value in the neighbourhood of 0.90 to 0.95, but in the carefully constructed tubes made for accurate work the value of C may be as high as 0.98 to 0.99.

Test Tanks. For small turbines a carefully calibrated weigh-bridge and test tanks can be used, but in stations where large units are installed, the problem of accurately measuring turbine condensate requires careful consideration. The usual method of weigh-bridge and weighing tanks cannot be adopted satisfactorily. The full load rate of flow of condensate may be as high as 200,000 lbs. to 250,000 lbs. per hour, and if the weighing apparatus is to be kept to a size that is easily transportable, it means that the time between filling a tank, and weighing and emptying, is far too short to allow accurate measurements to be made. Testing work can be greatly facilitated if permanent apparatus for the purpose is installed. An example of such a system is shown in Fig. 51. Two test tanks made of 1 in. boiler-plate, with welded joints and of 30,000 lbs. capacity each, are installed in a convenient position adjacent to the turbine and boiler-rooms. Each tank is fitted with a gauge-glass and scale. The scale may be marked off in feet or pounds, preferably in feet since corrections for temperature may have to be applied. The tanks are calibrated by filling with water which is then run into a tank on a weigh-bridge. The change-over valves on top of the tanks are so arranged that when one is being closed the other is simultaneously opened, thus ensuring the minimum interruption to the flow. With such a system it can be seen from the figure that turbine and boiler testing is then simply a matter of posting observers, there being an entire absence of the chaos usually attendant at such ceremonies. Another point worthy of note is that by means of the test tanks, water meters, boiler flow meters, etc., can be checked at any time. In fact, all testing work connected with the generating plant can be carried out without the necessity of breaking pipe-joints, erecting staging, and temporary apparatus, etc. When testing generating plant the results can be appreciably affected by observation time errors, and at all posts where readings have to be taken simultaneously with the test tank readings, an efficient signal system is necessary if these errors are to be eliminated or kept at a minimum. A bell or lamp signal system controlled from the test tank platform fulfils this purpose admirably. Reverting to automatic instruments for the measurement of condensate, there are many stations in which no apparatus for this purpose is installed. Also, there are cases where only one instrument is provided which measures the total condensate from all turbines

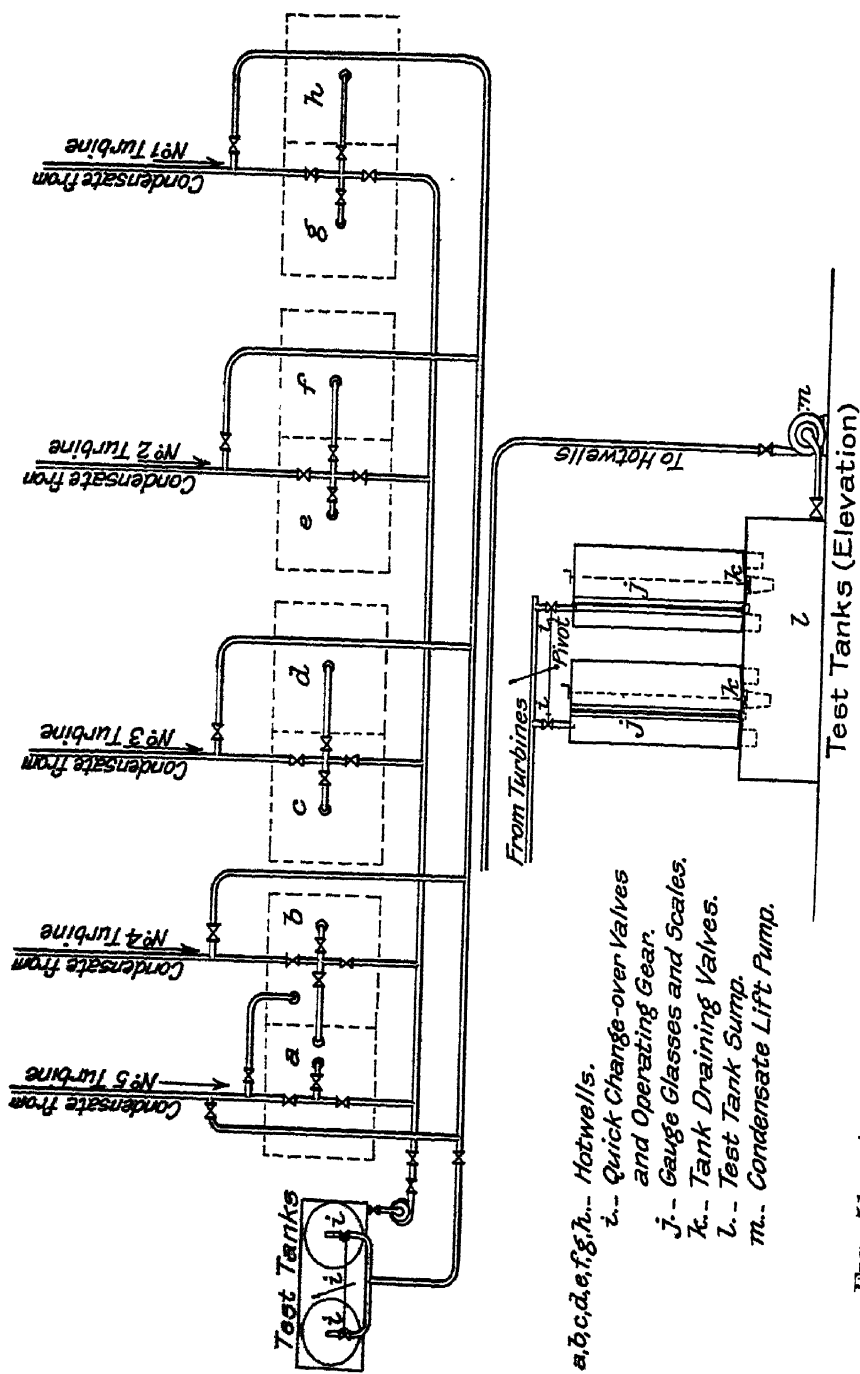


FIG. 51.—ARRANGEMENT OF TEST TANKS, HOT WELLS, AND CONDENSATE SYSTEM.

While this latter is certainly better than nothing at all, the engineers are to a certain extent handicapped in investigating the performance of individual turbines.

Steam Flow. The steam flow through a turbine can, however, be estimated, particularly at certain loads, by considering the first group or groups of nozzles to be a steam meter. The laws governing the flow of steam through nozzles, having profiles used in commercial design, have now been investigated to an extent enabling formulae to have been developed, by which the weight of steam discharged may be estimated. The application of such formulae requires the following necessary data—

- (1) Throat area of nozzle or nozzles.
- (2) Initial pressure before nozzle = P .
- (3) Specific volume, ft.³/lb. before nozzle = V (which is dependent on superheat).
- (4) Value of nozzle discharge coefficient (which is dependent on nozzle profile).

With reference to the above data (1) is easily estimated by direct measurement of the individual nozzles; (2) and (3) are derived from the turbine instrument panel and reference to standard steam tables. The value of (4) may be taken as 0.308 for commercial nozzles with sufficient accuracy for all practical purposes. In fact, it has been demonstrated in carefully conducted trials, in which the condensate was accurately weighed, that the following formula, incorporating the above data gave results within 2 per cent, after correcting the condensate value for condenser leakage and gland steam.

Pounds of steam per second per square inch of nozzle throat area—

$$0.308 \sqrt{\frac{P}{V}}$$

Fig. 52 is the above formula in graphical form over the range of steam pressures and temperatures likely to be met with in practice. An example will illustrate this method of determining the quantity of steam flowing through a turbine more clearly perhaps than the foregoing description.

How to Estimate Steam Consumption. Assume that an impulse turbine, controlled by three governor valves, two of which are open, is carrying a load of 14,000 kilowatts, and the following particulars of the governor valves and nozzle arcs

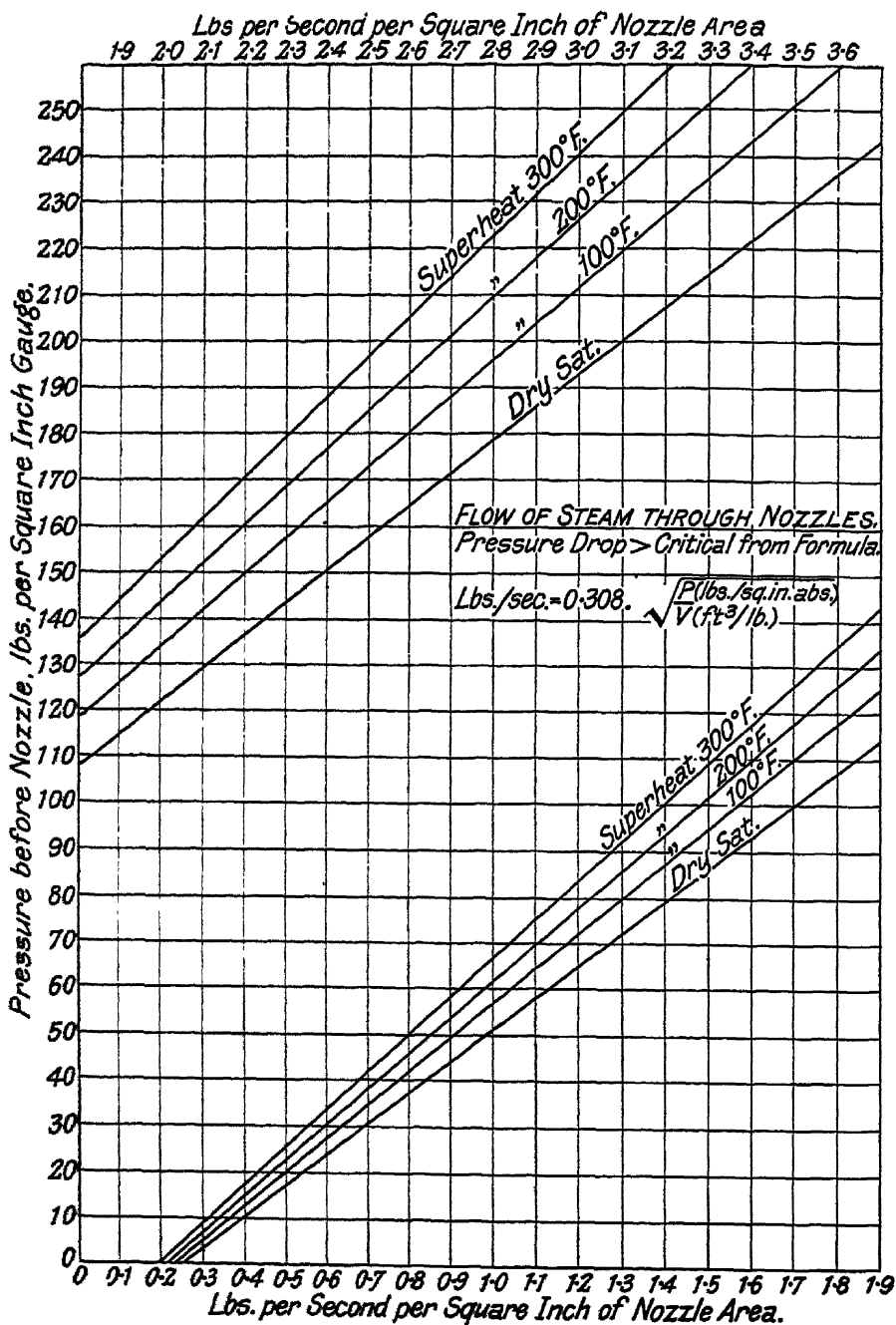


FIG. 52.

are known. The first governor valve controls an arc of 20 nozzles, the throat area of each nozzle being 0.5 sq. in., the total area is therefore equal to 10.0 sq. ins.

The second governor valve controls an arc of 10 nozzles, the throat area of each nozzle being 0.5 sq. in., the total area is therefore equal to 5.0 sq. ins.

Further assume that the following readings have been taken—

Pressure after first governor valve .	. 200 lbs. per sq. in. gauge.
	= 215 lbs. per sq. in. absolute.
Temperature after first governor valve .	600° F.
Pressure after second governor valve .	180 lbs. per sq. in. gauge.
	= 195 lbs. per sq. in. absolute.
Temperature after second governor valve	600° F.

Then from steam tables and chart (Fig. 52) the rate of flow per square inch of nozzle area per second through the first governor valve nozzles is 2.84 lbs. per second, and through the second governor valve nozzles is 2.59 lbs. per second. The rate of flow per hour—

Through first governor valve . . .	. 2.84 × 10 × 3,600
	= 102,240 lbs. per hour.
Through second governor valve . . .	. 2.59 × 5 × 3,600
	= 46,620 lbs. per hour.
Total . . . . .	. 148,860 lbs. per hour.
Turbine steam consumption . . . . .	. 10.63 lbs. per kilowatt

It should be borne in mind that the formula given is only applicable where the pressure drop across the nozzle is greater than critical. The best conditions under which the turbine steam flow can be estimated in the manner described is with full or nearly full load pressure before each group or groups of nozzles. The rates of steam flow at which these conditions exist will depend on the number of governor valves and the points at which they open.

It has already been pointed out that the load carried by the turbine bears a close relation to the rate of steam flow. Therefore, if the steam flowing through the first nozzles be estimated at the points when full or nearly full load pressure exists before each group or groups of nozzles, and the results plotted on squared paper against the corresponding loads carried by the turbine, the line thus obtained will represent fairly closely the Willan's line for the turbine, from which

the rate of flow and steam consumption for intermediate points can be determined.

The lines thus obtained, which can be arranged to show load against total steam per hour and steam consumption per kilowatt-hour, should be plotted on the same graph field with the line previously described, giving the relation between loads or steam flow and pressures after the first expansion. An example of such a combination of lines is shown in Fig. 53.

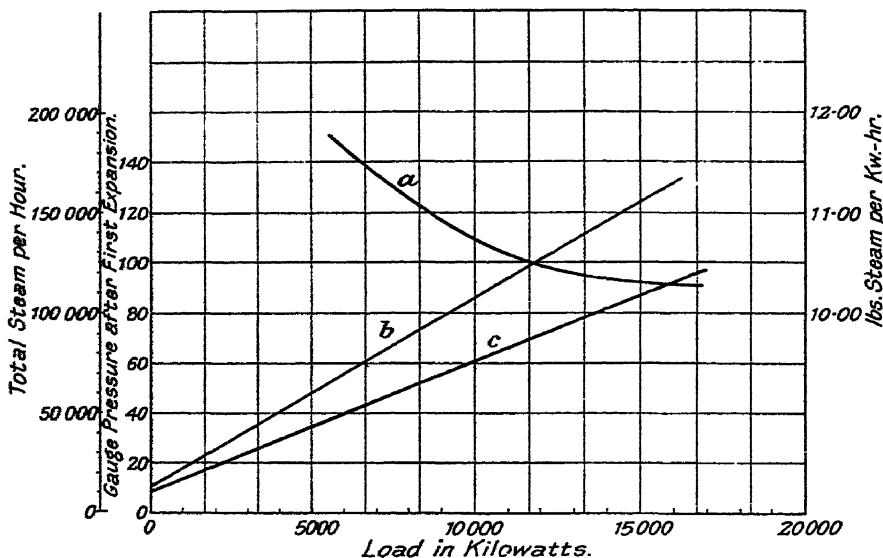


FIG. 53.

If a system such as has just been described is to be of any use in checking the daily performance of individual turbine units, readings of the turbine pressure gauges, etc., must be regularly taken and logged. The results obtained will, of course, be affected by the variations in steam pressure, steam temperature, and condenser absolute pressure. If desired, the correction factors usually supplied by the designers of the turbine can be applied to reduce the results to a standard basis for comparison. Under test conditions, of course, it is imperative that steam consumption figures be corrected to standard conditions. Consideration of the following will make this clear. It is practically impossible to maintain the specified initial and terminal steam conditions over the test periods, usually two hours for each load. It has been seen that steam consumption

is effected by variations in initial and terminal conditions, therefore it is necessary to correct the test results to the specified conditions, thus enabling a more correct comparison to be made between the actual and the guarantee consumption of the turbine. As has been stated, only the correction factors supplied by the designers should be used to correct to specified conditions, the steam consumption of a particular turbine. Typical correction curves have been given in Figs. 45, 46, and 47 and an example will make clear the application of the factors. Assume that the curves given in Figs. 45, 46, and 47 are for a turbine which has been run on test at half, three-quarter, and full load, and that the average actual conditions during the test were as follows—

	$\frac{1}{2}$ -load.	$\frac{3}{4}$ -load.	1-load.
Pressure, lbs. per sq. in. gauge	265	260	250
(corrected for gauge error)			
Total steam temperature, degrees F.	660	645	640
(corrected for thermometer errors)			
Vacuum, inches of mercury	28.55	28.46	28.35
(corrected for temperature)			
Barometer, inches of mercury	29.50	29.50	29.50
(corrected for temperature)			
Uncorrected Steam consumption	11.18	10.98	10.69
(lbs. per kilowatt-hour)			
Then vacuum, corrected to	29.05	28.95	28.85
(barometer at 30 ins. mercury)			

	$\frac{1}{2}$ -load.	$\frac{3}{4}$ -load.	1-load.
And corrections expressed as percentages			
(from Figs. 45, 46, and 47)—			
Pressure corrections	+ 0.78	+ 0.54	0.00
Steam temperature corrections	+ 0.68	+ 0.45	+ 0.75
Vacuum corrections	- 0.90	- 2.20	- 2.80
Total corrections	+ 0.56	- 2.11	- 3.55

Before applying the foregoing corrections it should be pointed out that the condensate and electrical output, from which the steam consumption is calculated, should be corrected for condenser leakage, steam or water for turbine glands, and electrical instrument and instrument transformer errors respectively.

CHAPTER VIII

CONDENSERS AND AUXILIARIES

Condenser Leakage. There are various methods of determining condenser leakage, but none of them give results that can be called accurate. If the circulating water is of a highly saline nature it may be possible from chemical tests of the condensate and circulating water, and from a knowledge of the ratio of circulating water to steam condensed, to estimate the percentage of circulating water leaking into the condensate. The dionic test, previously described, has been suggested as a means of determining condenser leakage, but after numerous trials this method, in the author's opinion, cannot be adopted with any degree of success. The best method is to carry out a special leakage test on the condenser and then actually weigh the leakage water. This test can be carried out as follows. All suspicious sources from which water can leak into the condenser are first of all blanked off. The steam should be shut off from the turbine, with the exception of gland steam, which can be measured by a method which will be described later.

The water-level in the condenser as indicated by the condenser gauge-glass should be easily observable, and the extraction pump suctions blanked off. If these pumps are driven from the same shaft as the air pump, the couplings should be broken. This remark only applies in the case of rotary air pumps. With steam on the turbine glands a vacuum is then built up in the condenser and when approximately running conditions have been reached, the condenser water-level is checked and marked on the condenser gauge-glass and a note taken of the time. After running for a given period, preferably not less than one hour, the water-level is again noted and marked, the time checked, and the air pump stopped and things brought back to normal. The water in the condenser is then run from the condenser drain and weighed until the level is reached at which the leakage test was started. Then, assuming that the duration of the test was one hour, the weight of water minus the weight of steam or water used for gland sealing, will represent the condenser leakage in pounds per hour.

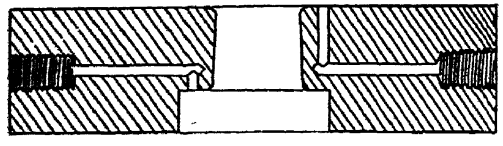
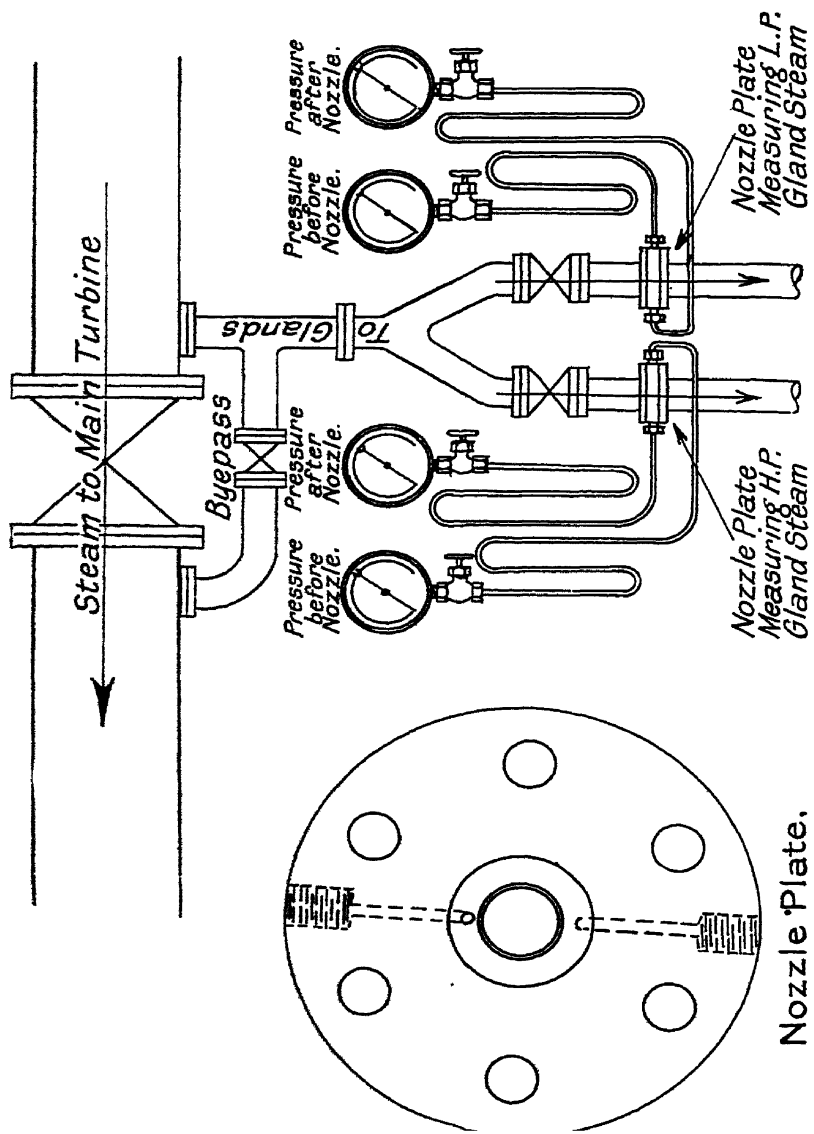
Steam Used by Auxiliaries. If steam jets are used either for condenser air extraction in place of a rotary or reciprocating air pump, or as an augmentor jet, the steam consumption of these units can be estimated from either the formula for the flow of steam through nozzles or from Fig. 52. In the same way, either the formula or the chart, can be employed to calculate the steam consumption of turbine-driven steam auxiliaries. By the construction and use of a few nozzle plates, to fit the different sizes of auxiliary steam pipes, quite a large number of power station steam flow measurements can be determined in quite an inexpensive manner. The pressure drop across the nozzle must be greater than critical, but a few experiments will soon determine the most useful size of nozzle and nozzle plates to use. Fig. 54 shows one method of construction and adoption of nozzle plates for the measurement of turbine gland sealing steam.

Before leaving this part of the subject connected with steam consumption, stress must be laid upon the fact that the control-room engineer can, if more than one turbine is in operation, help greatly towards keeping the steam consumption figure at a minimum by the intelligent distribution of the load on the turbines, so that full or nearly full pressure is maintained before the groups of nozzles which are in operation.

Condenser Measurements and Condenser Performance. Poor condenser performance is one, if not the greatest, cause of high turbine-room steam consumption. The low absolute pressures necessary for efficient turbine operation have led to great improvements in methods of condensation, and the modern turbine condensing plant, if intelligently operated and well maintained, need not be the grave of all our economies.

It is intended in this section to deal with only the type commonly referred to as surface condensers. Owing to the necessity of only chemically pure, air-free condensate being fed to the boilers, the majority of condensers employed on power station work are of the surface type.

The elementary parts of a surface condensing plant are the condenser (which is made up of the condenser shell, water boxes, tube plates, and tubes), the circulating pump, and the air extraction, condensate extraction, and condensate lift pumps. Fig. 55 is an example of a modern condensing plant. Condensers for the large turbine units that are now installed are usually constructed in sections, and assembled and tubed on site. Owing to difficulties due to expansion they are



Section through
Nozzle Plate.

FIG. 54.

seldom supported on foundations, but are placed on feet constructed of helical springs. In some cases the condenser is hung directly from the exhaust flange of the turbine.

It is customary to pass the circulating water through the condenser at least twice, and for this purpose the water boxes are built in two or more sections as the case may be: the bottom section receiving the water from the circulating pump, and the top section discharging it from the condenser to the outlet pipe. Such an arrangement is termed counterflow. It has been demonstrated that this method gives a better transference of heat than with parallel flow: the maximum condensation being obtained at the top of the condenser, due to the fact that the upper tubes are driest and swept clear of air films by the incoming steam, and although the temperature of the circulating water is higher than in the lower tubes, condensation is greater. A nest of tubes opposite the air pump suction are usually covered by a baffle plate, thus ensuring that cool air will be handled by the air pump.

Air Extraction. Steam as presented to a turbine always contains a small proportion of air, being in the neighbourhood of one part in 4,000 by weight. As it is impossible to construct a commercial condenser to be perfectly air-tight, the quantity of air entering the condenser with the steam is increased by small leaks at joints in the turbine frame and condenser body. The removal of this air is the function of the air pump. It is due to the presence of this air in steam, together with leakage air, that condenser auxiliaries are considerably complicated, it being necessary that the air extraction plant maintains the lowest partial air pressure inside the condenser shell.

In general, with a modern well-maintained condenser, the air extraction plant will be required to handle from 5 to 6 lbs. of air for every 10,000 lbs. of steam per hour up to 150,000 lbs. of steam per hour; above this figure the air quantity may be taken at 4 lbs. for every additional 10,000 lbs. of steam per hour.

Condensate extraction and condensate lift pumps call for little comment, except that they present special problems of their own to centrifugal pump manufacturers.

Air extraction plant may be divided into three general classes, viz. reciprocating, rotary, and steam-jet. The first named class may be further sub-divided—

(a) Reciprocating pumps on the simple system in which the condensate and air are taken through the one suction

pipe to the barrels of the air pump, the air being discharged by a vent-pipe to atmosphere, and the condensate discharged to the suction of the hot well pump, which is usually driven by the same crank shaft as the plungers of the air pump. In some instances with this system a vacuum augmentor is used, this being a steam-jet discharging into a diffuser cone to the air pump suction, the exhaust steam from the jet being condensed in some form of small condenser using condensate for cooling water in which the heat of the exhaust steam is regained in the condensate. The steam-jet acts as a compressor and supplies the air to the air pump barrels at a higher absolute pressure than exists in the condenser: thus by decreasing the volume per pound of air a greater weight of air can be handled by the pump and its volumetric efficiency increased.

(b) Reciprocating pumps on the wet and dry system. Air pumps of this class have separate barrels for handling the condensate and air, the Weir Dual system being typical of this type.

With the necessity for the high vacua of modern practice, the limiting features of the reciprocating type of air pump were realized and the rotary pump developed to its present state of efficiency and reliability. All rotary air pumps work on the principle of a series of water-jets or laminations, discharged from the periphery of the impeller, being employed to entrain and compress the air. This type of pump takes longer to reduce the absolute pressure in a vessel of any given size, in comparison to the other two types, but with good conditions it will maintain the absolute pressure in a condenser within a few hundreds of an inch of mercury of the theoretical absolute pressure.

The power taken to drive this type of pump is considerably more than that required by the reciprocating type, but in comparison to these the cost of maintenance is very much lower, and given periodic attention the rotary type of air pump will maintain its efficiency practically indefinitely.

The Ejector. The simplest and most flexible type of apparatus for handling condenser air is undoubtedly plant of the steam-jet type. The principle of operation consists of projecting steam at a high velocity in the form of a jet, through a space where the air has collected, into a convergent compression pipe. The air is entrained by the surfaces of the steam-jet, and the object of the steam nozzle is to obtain a jet issuing at a maximum speed, and such as will put in motion and

entrain the maximum volume of surrounding air or gases, the combined steam and air then passing into the convergent pipe and becoming compressed. The kinetic energy is then transformed into potential energy, whereby the steam and air is discharged against a pressure considerably higher than that in the preceding air chamber. As it is practically impossible to compress efficiently the air at absolute pressures less than 3 ins. of mercury and discharge the same against atmospheric pressure in the one stage, steam ejector air pumps are almost

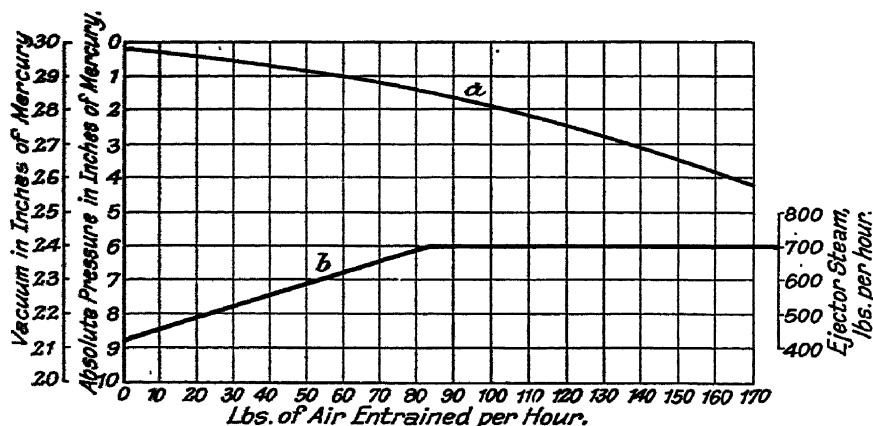


FIG. 56.—STANDARD WORKS TEST CHART.

(a) Vacuum curve

(b) Steam consumption

invariably made up of two stages. They are manufactured in various combinations, sometimes with an auxiliary condenser interposed between first and second stages of compression. The performance of one type of steam ejector for air extraction can be followed from the example of a standard works test chart in Fig. 56. Detailed descriptions of the various types of condenser auxiliaries will be found in any good, up-to-date text-book.

Heat Rejected to Condenser. The heat rejected to the condenser per pound of steam flowing through the turbine depends upon the efficiency of the turbine and condensing plant. For a well-maintained and competently operated unit the value will vary between 950 to about 1,050 B.T.U.'s per lb. of steam condensed.

The quantity of heat to be abstracted per pound of working fluid is a function of its state at the exhaust flange of the turbine. In general, the condition of the steam at this point

is of fractional quality, and for high pressure turbines the value may vary between limits of 0.85 to 0.95.

Each pound of fluid entering the condenser therefore contains a definite heat quantity corresponding to its state, and after condensation, will have as water a temperature lower than the corresponding state point and dependent on condenser design. It is impossible in commercial design to avoid under-cooling. In the ideal condenser receiving air-free steam, and having no steam friction drop across the tubes, the condensate would have a temperature corresponding to the pressure at the exhaust flange. Owing to the steam friction and the unavoidable presence of air, due to the impossibility of designing air extraction plant having 100 per cent efficiency, the ideal conditions cannot be realized in practice. For instance, in the case of an ideal condenser having an absolute pressure at entry of 1.0 in. mercury, the temperature of the condensate would be 79.5° F. This temperature corresponds to the pressure of 1.00 in. mercury absolute. In practice, owing to steam friction and the presence of air, the conditions in a good commercial condenser might possibly be—

(a) Absolute pressure at inlet to condenser	1.00 in. Hg.
(b) Steam friction drop across tubes	0.15 in. Hg.
(c) Partial air pressure at bottom of condenser	0.15 in. Hg.
(d) Vapour tension corresponding to temperature of condensate	0.70 in. Hg.
(e) Temperature of condensate would be	68.5° F.

It will be noted that the pressure (a) at entry to condenser is the sum of (b), (c), and (d), which results in the condensate having a maximum temperature allowable of 68.5° F., whilst the inlet temperature of the working fluid is 79.5° F. From the foregoing it will be seen that the under-cooling is 11° F. for the case given. It will be further seen that the heat to be absorbed by the circulating water is not only the latent heat per pound of working fluid, but includes a further quantity necessary to under-cool the condensate. It is most important to note, the heat rejected in a condenser is not the value of the latent heat at the temperature of entry as obtained by direct reference to standard steam tables. There are various approximate and easily applicable methods of determining the heat content rejected per pound of working fluid entering the condenser.

If the steam consumption of the turbine, initial and final

conditions of the steam, and temperature rise of circulating water be known, then by assuming a value for alternator efficiency and bearing losses, a fairly close approximation can be arrived at. An example will illustrate this method of determining the heat rejected to the circulating water per pound of steam condensed.

Assume—

Total steam condensed per hour	.	.	150,000 lbs.
Steam consumption of turbine	.	.	10.75 lbs. per kw.-hr.
Initial pressure	.	.	260 lbs. per sq. in gauge
Initial temperature	.	.	650° F.
Temperature of condensate	.	.	75° F.
Heat content of condensate	.	.	43 B.T.U.'s per lb.
Temperature rise of circulating water	.	.	12° F.
Assumed alternator losses	.	.	4%
Assumed bearing losses	.	.	2%

Then from steam tables—

Total initial heat in steam from 32°F., 1,337 B.T.U.'s per lb.

Heat utilized in mechanical work $\frac{3414}{0.94 \times 10.75} = 337$ B.T.U.'s per lb.

Note.—3414 = B.T.U. equivalent of K.w.

.94 = 1.00 - (alternator losses + bearing losses).

Then heat rejected to circulating water—

1337 - (heat in condensate + 337) = 957 B.T.U.'s per lb.

It should be emphasized that the accuracy of the temperatures or temperature rises in condenser work is of the utmost importance in the estimation of the various heat transmission factors, pressures, and efficiency calculations. For instance, in practice with a rise in temperature of 10° F. in circulating water at partial load, an error of 1° F. means an error of 10 per cent. For the estimation of condenser efficiencies, etc., it is really essential that thermometers be employed reading to at least one-fifth of a °F. These should not be used in ordinary thermometer pockets, but should be inserted naked, through specially constructed glands into the circulating water or condensate as the case may be.

Thermal Efficiency of Turbine. From the foregoing calculation in relation to the heat rejected, a considerable field of information is now open. The temperature rise of the circulating water is 12° F. Knowing this, and also the heat per pound of steam rejected to the circulating water, the quantity of circulating water flowing through the condenser may be

calculated. For every pound of steam condensed, each pound of circulating water (assuming the specific heat of the circulating water to be 1.0 at that temperature), carried away 12 B.T.U.'s, therefore the ratio of circulating water to steam (usually written $W : S$) is 957 : 12, or simplifying 80 : 1. The total circulating water passing through the condenser per hour is therefore 80 times the rate of steam flow per hour through the turbine, i.e.—

$$\begin{aligned} & 150,000 \times 80 \\ &= 12,000,000 \text{ lbs. per hour} \\ &= 20,000 \text{ gallons per minute.} \end{aligned}$$

Another point worthy of note is that the thermal efficiency of the turbine can be estimated from the percentage of heat per pound of steam utilized in doing mechanical work, to the total heat per pound of steam from and at 32° F. supplied to the turbine—

$$\frac{337 \times 100}{1337} = 25.2\%$$

This must not be confused with the efficiency ratio of the turbine, sometimes termed the thermo-dynamic efficiency, which will be referred to presently.

Use of the Entropy Diagram. The heat rejected to the condenser may also be estimated in a very simple manner by means of a total heat-entropy diagram. If this method is used it is necessary to know the initial steam pressure, initial steam temperature, final absolute pressure, and the turbine efficiency ratio. Reference to Fig. 57 will make the method clear. From the initial conditions of the steam the state point *A* is determined : from this point the adiabatic line is dropped until it intersects the pressure line corresponding to the observed absolute pressure, i.e. point *B*. Then taking *AB* as unity, the efficiency ratio is scaled off as a fraction of *AB* as represented by *AC* in the diagram. From a horizontal projected from *C* to the total heat scale, the heat rejected to the condenser per pound of steam is then read off.

Further, from the intersection of this horizontal with the absolute pressure line, the approximate condition curve for the turbine can be drawn by joining the point of intersection with the initial state point, i.e. *AD*, Fig. 57.

Efficiency Ratio. The efficiency ratio often referred to as the thermo-dynamic efficiency of the turbine, is the ratio of the actual mechanical output available at the turbine coupling,

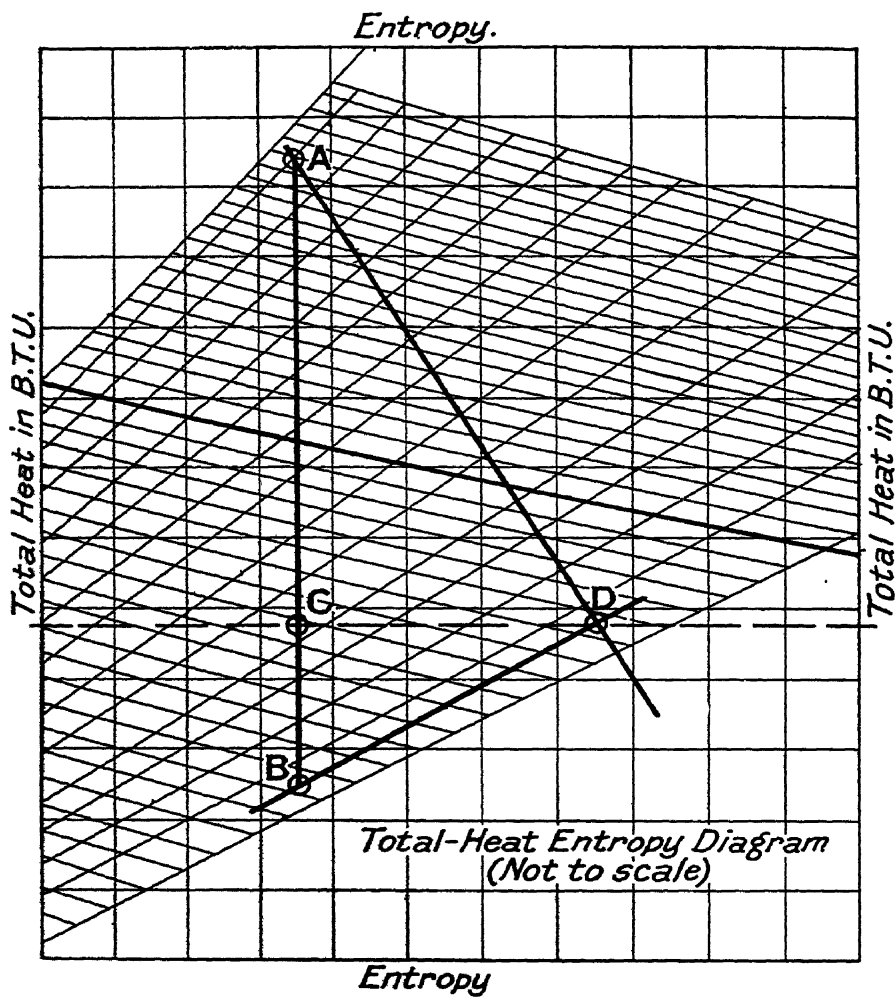


FIG. 57.

to the mechanical work available from an ideal turbine on the Rankine cycle, working between the same limits of temperature and pressure. This factor covers all the internal losses such as blade and disc friction, fan losses, diaphragm or tip leakage, together with all external losses such as bearing friction, power absorbed by governor and oil pump drives, coupling windage, etc.

$$\text{Efficiency ratio} = \frac{He}{Hr}$$

where He = B.T.U. equivalent of kw.-hour = 3414.

and Hr = actual adiabatic heat drop = $h \times c \times n$.

h = actual adiabatic heat drop per lb. of steam.

c = steam consumption, lbs. per kilowatt-hour.

n = 100 minus (alternator losses plus bearing losses).

For the large turbines now in operation the value of the efficiency ratio with the unit in good condition should be, under the most economic conditions, in the neighbourhood of 75 to 80 per cent.

CHAPTER IX

CIRCULATING WATER AND CONDENSER CONSTANTS

ONE of the greatest problems in modern power station design is the supply of circulating water for condensation purposes. At normal full load the ratio of circulating water to steam condensed varies approximately between 70 : 1, and 90 : 1, which means that for the large plants now in operation, or in course of erection, a supply has to be assured from which at certain times anything from 100,000 to 200,000 gallons per minute will be drawn.

Where this supply can be taken from a river, canal, or the sea the problem is greatly modified. As will be seen presently, efficient condenser performance is practically entirely dependent upon the inlet temperature and quantity of circulating water, and every precaution must be taken to ensure a constant and reliable supply.

Screening. Efficient water screening plant is an absolute necessity, especially in cases where the circulating water is drawn from a river having its source in, or flowing through, wooded country. Fallen leaves, brought down by high water in autumn or during the winter will prove a dangerous source of trouble unless the screening plant can efficiently deal with them. As small a quantity as a bucketful of leaves getting past the screening plant, is sufficient to put even the largest unit out of service.

Where the supply of water is taken from a canal or tidal river, trouble occasionally arises due to an absence of flow in the former and the condition of the tide in the latter, causing undesirable rises in the temperature of the inlet circulating water.

In the consideration of the layouts of large power station plants, very careful attention should be paid to the circulating water service. Wherever possible a syphonic system should be employed in order to reduce power of pumping to a minimum.

Cooling Towers. Where a natural supply of cooling water is unobtainable, the circulating water is cooled by a combination of artificial and natural means in what is termed a cooling tower. It will be obvious from what has been said, that the

cost of a supply of circulating water from the town mains would be prohibitive. A cooling tower is usually a wooden structure erected over a reservoir in the form of a pond. The internal structure of the tower is usually a network of small wooden troughs and laths.

The circulating water is drawn from the pond, and after passing through the condenser is discharged to a point near the top of the tower into the first set of small wooden troughs. It overflows from these and in falling to the pond is broken up by the wooden network in the tower. The tower is open at the top and bottom, and, consequently when in operation, a current of air is drawn in and flows up through the falling water, intimately mingling with it, removing a certain amount of its heat, and reducing its temperature. Towers of this description are termed natural draught towers to distinguish them from another type, employing fans to increase the intensity of the draught. The latter class are usually referred to as forced draught towers. The purpose of a cooling tower is the removal of the heat taken up by the circulating water in its passage through the condenser.

Cooling of the water is practically entirely by evaporation, the effect of conduction and convection being negligible; therefore the efficient performance of a tower in a good state of maintenance depends upon the humidity of the atmosphere, and the best performance will be obtained when the atmosphere is warm and dry. From this it will be seen that a certain proportion of the circulating water is being continually lost, and this proportion will have to be replaced from an outside source. Owing to the necessity of having to lift the water to the top of the cooling tower, the power absorbed by the circulating pumps is considerably in excess of what would be required to drive similar auxiliaries if a natural supply of water was available. Generally speaking, where cooling towers are employed, and the condenser auxiliaries are electrically driven, variable speed motors should be employed to drive the circulating water pumps, so that the quantity of water can be regulated in accordance with the load on the turbine. Another point worth noting in regard to cooling tower stations is that condenser tube trouble, due to corrosion, may occur if the towers are situated in an industrial neighbourhood where the atmosphere may be contaminated by objectionable gases from chemical, iron, and gas works. With a given set of conditions, and a definite quantity of circulating water

flowing through the condenser, the quantity of steam condensed determines the rise in temperature of the circulating water ; or, on the other hand, with a definite amount of exhaust steam entering the condenser, the quantity of circulating water determines the temperature rise. Further, for a given set of conditions and with a constant quantity of circulating water, the inlet temperature of the circulating water determines the absolute pressure in the condenser.

Relations between Condenser Vacuum, Steam Flow, and Inlet Water Temperature. For each turbine the engineer-in-charge, therefore, should determine the various values of condenser absolute pressure for different rates of steam flow over the range of circulating water inlet temperatures met with in practice. These curves can be compiled from the designer's guarantee figures, test results, or the best values found from operating experience on commercial load, and when completed should be framed and fixed near the mercury vacuum columns. If this is done for each turbine a glance at the actual indicated conditions, and reference to the curves, will show instantly whether or not condenser performance is being maintained at the most efficient figure. Fig. 58 is an example of curves such as described. These were plotted from the best results obtained under ordinary operating conditions.

Condenser Absolute Pressures. The effect of terminal absolute pressure on turbine steam consumption has already been enlarged upon, and the importance emphasized of maintaining the terminal absolute pressure at its most economical value. The variable factors affecting the terminal absolute pressure and over which the operating engineer can exercise some control will now be considered.

The absolute pressure carried in a condenser varies very closely with the mean of the inlet and outlet circulating water temperatures. The mean temperature of the outlet and inlet circulating water is dependent upon the temperature rise, which in turn is influenced by the quantity of circulating water or the quantity of steam entering the condenser, therefore these variables have a direct effect upon the total absolute pressure in the condenser. Reference has been made to the fact that in striving for low values of absolute pressure, the extra power required for pumping must be taken into account when considering any gain on steam consumption. This can be demonstrated if the circulating pump is electrically driven

and a watt-meter connected to the motor leads. It will then be found that the increases necessary in the quantity of the circulating water to produce decreases in absolute pressure,

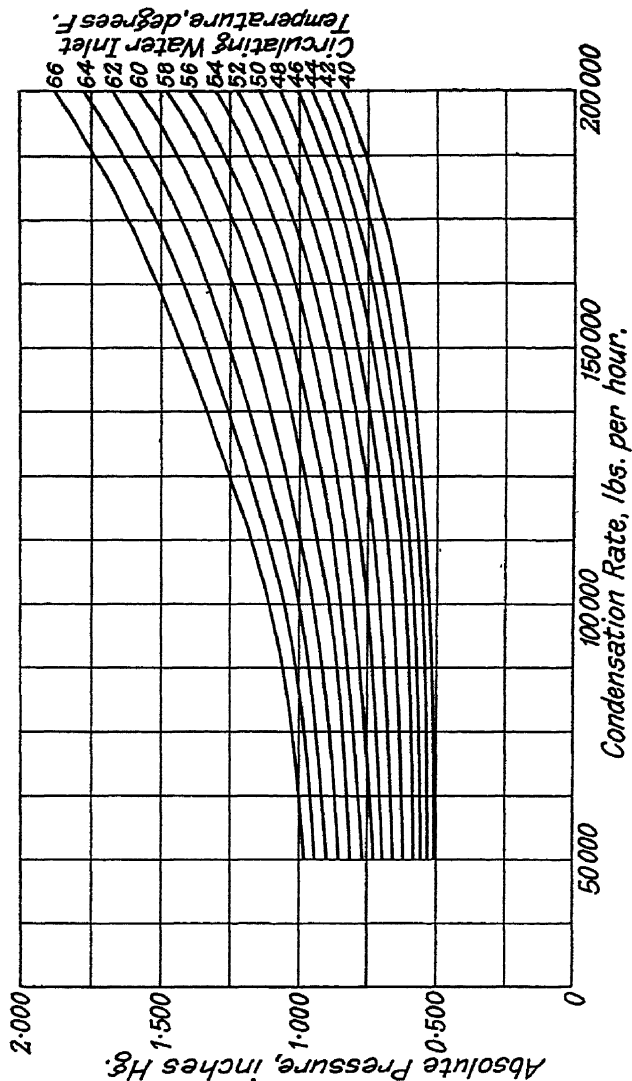


FIG. 58.

With a constant quantity of circulating water (22,500 galls. per min.) absolute pressure at top of condenser, by mercury column, should never exceed the value shown, for a given circulating water inlet temperature.

become progressively larger. This is due to the fact that for each decrease in absolute pressure the corresponding temperature decrease is greater.

In a good condenser from 7 to 10 lbs. of steam are condensed

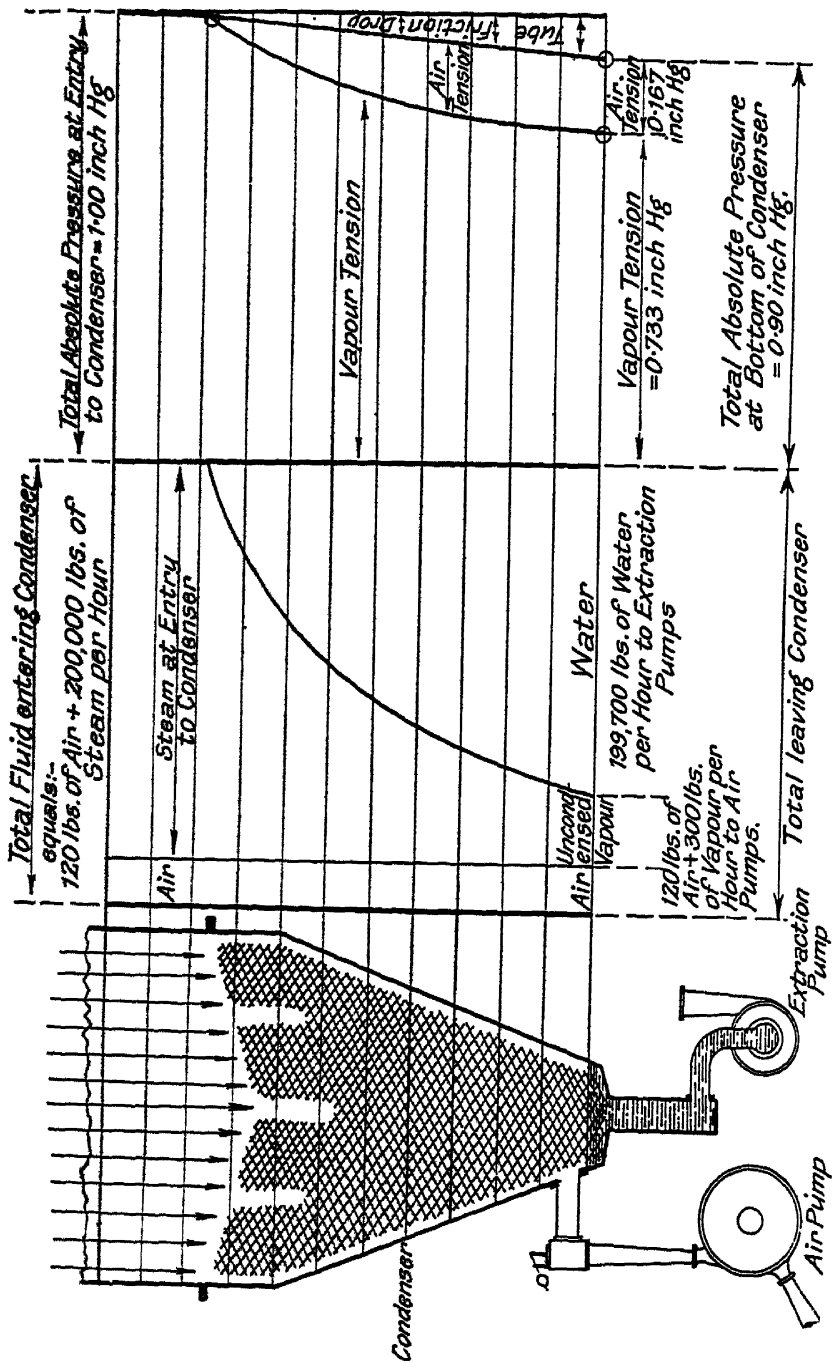


FIG. 59.

per square foot of cooling surface per hour, and in commercial operation a ratio of circulating water to steam condensed, in the order of 70 or 80 : 1, is representative of good practice.

The total absolute pressure in a condenser is the sum of the pressure, due to the steam or water vapour, and the pressure due to the air which is always present. Dalton's law, which may be written as follows, states that: "A mixture of gases at a common temperature confined in a vessel, will exert on the boundary of the vessel containing the mixture, a pressure which is equal to the sum of the pressures which each gas of the mixture would exert separately if it alone occupied the vessel." In a condenser the mixture of steam or water vapour, and air, the pressure exerted by the steam or vapour is the same as the pressure it would exert if there were no air present, and the pressure exerted by the air is the same as it would exert if there were no steam present. The total absolute pressure throughout a well-designed condenser is practically constant, but the relation between the partial pressures vary considerably.

In Fig. 59 an attempt has been made to show the conditions existing throughout a condenser in operation. It will be seen that at entry to the condenser the percentage of air is so small that the partial pressure is practically negligible, being in the neighbourhood of only a few thousandths of an

	1st Test.	2nd Test.	3rd Test.
Lbs. of Steam condensed per hour . lbs.	117,000	163,500	199,500
Steam pressure at Stop Valve lbs. per \square "g.	271	265	263
Steam Temperature at Stop Valve . . °F.	673	657	665
Exhaust Steam Temperature . . °F.	79.3	85.8	89.4
Standard Barometer . . ins. of mercury	29.746	29.696	29.832
Vacuum at Top of Condenser ins. of mercury	28.720	28.443	28.443
Vacuum at Top of Condenser mm. of mercury	729.5	722.6	722.46
Vacuum at Bottom of Condenser ins. of mercury	28.810	28.661	28.819
Vacuum at Bottom of Condenser mm. of mercury	731.8	728.0	732.0
Vacuum at Top referred to Barometer of 30.00 ins. mercury	28.974	28.753	28.611
Vacuum at Bottom referred to Barometer of 30.00 ins. mercury	29.064	28.965	28.987
Condensate Temperature, bot. of Condenser °F.	63.0	67.9	76.0
Temperature of Vapour at Air-pump suction °F.	60.0	61.0	62.4
Circulating Water Inlet Temperature . °F.	58.0	58.0	57.6
Circulating Water Outlet Temperature . °F.	65.4	69.5	72.0

inch of mercury. The curves shown in the diagram are assumed, as their form is greatly influenced by condenser design. One point made clear from the diagram is the necessity for instrument connections being on the one plane. The table shown on p. 193 is the minimum of measurements necessary for checking condenser performance.

From the foregoing data the following results are computed. The values given in this example must not be looked upon as representative of the best practice, and are given here merely to illustrate how the results are arrived at—

	1st Test.	2nd Test.	3rd Test.
Temperature Rise of Circulating Water . °F.	7.4	11.5	14.4
Total Absolute Pressure at Bottom of Condenser ins. mercury	0.936	1.035	1.013
Vapour Tension corresponding to Temperature of Condensate . ins. mercury	0.576	0.684	0.897
Air Tension at Bottom of Condenser ins. mercury	0.360	0.351	0.116
Friction Drop across Tubes and Baffle ins. mercury	0.090	0.212	0.376
Average Circulating Water Quantity gals. per min.	24,000	23,000	23,000
Heat rejected to Circulating Water per Pound of Steam . B.T.U.'s	978	952	958
Steam Condensed per Square Foot of Cooling Surface per Hour . lbs.	4.5	6.3	7.7
Mean Temperature Difference . °F.	17.4	21.6	23.8
Condenser "K" B.T.U.'s/°F./square foot/hour	253	278	310

As will be seen from this example of a condenser test, readings have been taken with the condenser handling three different steam weights. By doing so, it is possible to finally express the performance of the condenser in a graphical manner by means of curves, as will be shown later. The outstanding points requiring attention, made apparent from the results tabulated above, are: the condensate is considerably undercooled at the lower loads; and the rapidly decreasing air tension, as the steam weight handled by the condenser increases, indicates a leakage of air at the lower loads. Broadly speaking, it can be stated that the closer the absolute pressure corresponding to the temperature of the condensate is to the total absolute pressure, the better will be the performance of the condenser.

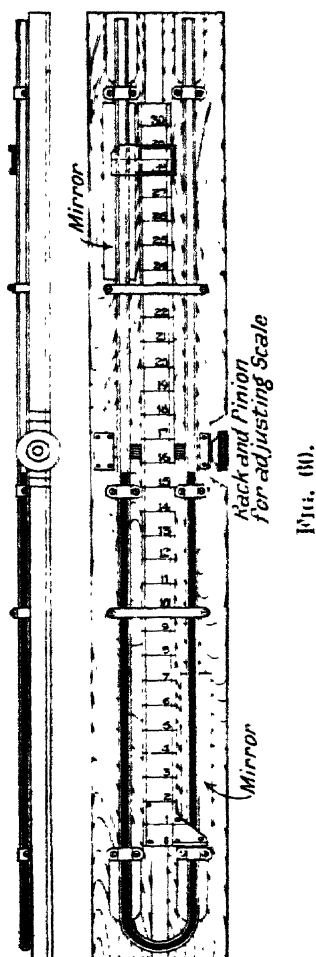
For test purposes the temperature measurements can be

made quite satisfactorily with good thermometers, but as already stated these must be graduated as finely as possible and fitted as previously described. In daily operating practice, when condenser readings are logged half-hourly, it is much better to install thermocouples at the necessary points, the leads being taken to a plug board and indicator on the turbine instrument panel, as shown in Fig. 49.

For the measurement of absolute pressure only mercurial U-tubes can be relied upon, and if these are carefully made and erected, and used in conjunction with the type of thermometer previously referred to, very accurate condenser results can be obtained. Fig. 60 shows a reliable form of U-tube for the measurement of absolute pressure. The tube is made from good quality glass and must be of even bore throughout. It is mounted on a wooden base into which mirrors are fixed at the points, coincident with where the working level of the mercury is likely to be. A dovetail groove runs the length of the wooden base and an adjustable scale is fitted into the groove. A section of the dovetailing forms a rack which engages the adjusting pinion, operated by the milled wheel at the side of the instrument. The upper part of the scale carries a vernier attachment. The instrument may appear expensive but in reality it can be made at a cost of a few shillings and, moreover, can be absolutely relied upon.

The ordinary type of meter stick, which can be purchased at any laboratory supply store, makes a very good scale. It should be fitted with a brass toe piece, as shown in the Fig., so that the zero can be accurately set to the lower level of the mercury.

Very accurate results can be obtained by recording the



values of the mercury height in millimeters and, if desired, these can be converted to equivalent inches of mercury at the end of the test or other period. For the measurement of small pressure differences, such as the drop across the condenser due to tube and baffle friction, it is advisable, where accuracy is desired, to measure this pressure drop in inches or millimeters of water.

For comparative purposes at the end of the test, it is a simple matter to convert the values to inches or millimeters of mercury.

The measurement can be made with the type of "U" tube just described, one leg being connected to a "T" piece in the top of the condenser connection, and the other leg connected to a similar fitting at the point where the bottom of the condenser measurements are made. It should be kept in mind that all metal and rubber tube connections to the condenser instruments must be kept absolutely air tight, the points where joints are made receiving special attention.

Necessity for Efficient Air Extraction. Another point made clear by the diagram, Fig. 59, is that efficient condenser operation necessitates as complete removal of the air as is possible, and this emphasizes the need for the condenser and air extraction plant being maintained at all times in a high state of repair. The presence of air greatly retards the rate of condensation, increases the absolute pressure in the condenser, consequently affecting the steam pressure in the turbine and the coal consumption of the station. The condenser air conditions can be checked in a few minutes. Assume that the temperature of the condensate was 75°F. , and that the vacuum at the bottom of the condenser was 29 ins. of mercury with a barometer of 30 ins. of mercury.

Then from the steam tables the vapour tension corresponding to 75°F. is 0.873 ins. of mercury; therefore, as the total absolute pressure is 1 in. of mercury, the partial pressure of the air at the bottom of the condenser is 0.127 in. of mercury. The partial pressure of the air is a criterion of air pump performance, and a good pump of the rotary or ejector type should maintain the partial air pressure as low as 0.05 to 0.10 in. of mercury.

Infiltration of Air. The condenser shell must be kept air tight, and in cases where the low pressure end of a turbine is built up of sections, care must be taken to prevent air infiltration at this point. Any air pump running at a constant

speed has a definite volumetric capacity, and unless these sources of air leakage are carefully watched, a good pump may be condemned as inefficient in the removal of air, while the real trouble is that the pump is operating heavily overloaded. It is, however, a simple matter to apply certain tests, depending upon the type of air extraction plant, to ascertain if the maximum amount of air is being handled. The most simple method is to run the air pump with the suction to the condenser closed; artificial air leaks of increasing magnitude are then opened into the suction of the pump, to which is also connected a mercury column. The artificial air leaks can be in the form of nozzles, the throat areas of which are known, or they can be made in the form of diaphragms. The latter are very useful in determining the amount of air handled by the air pumps of a condenser operating on commercial load. The method can only be applied where rotary air pumps are employed using a closed sealing tank system, the nozzle diaphragm being connected to the vent pipe from the sealing tank.

The lbs. of free air at 29.92 ins. of mercury absolute pressure and 62°F., flowing through a nozzle, the pressure drop being greater than critical, can be calculated from the following formula—

$$W = 1.124D^2 \frac{B}{\sqrt{T}}$$

where W = lbs. of free air per hour.

D = Nozzle throat diameter in millimeters.

B = Barometer height in inches of mercury.

T = Air temperature, absolute deg. F.

Condenser performance can be very clearly illustrated by plotting curves from the various readings. It is possible to express all the values in terms of absolute pressure, and this has been done in Fig. 61. The curves shown are representative of very efficient performance indeed, and were compiled from readings taken on the condenser of an 18,750-kw. turbine. The values can be read in either degrees F. or in absolute pressures expressed in inches of mercury. The difference between curve b and curve b^1 represents tube friction drop, and the difference between curve b^1 and curve c represents the partial pressure due to air, which in this case is 0.08 in. of mercury at full load.

Generally speaking, under good conditions the difference between the temperature at the turbine exhaust and the temperature of the condensate at full load should be in the neighbourhood of 5 to 8° F., with a further difference of 5° F. between the temperature of the condensate and the temperature of the outlet circulating water.

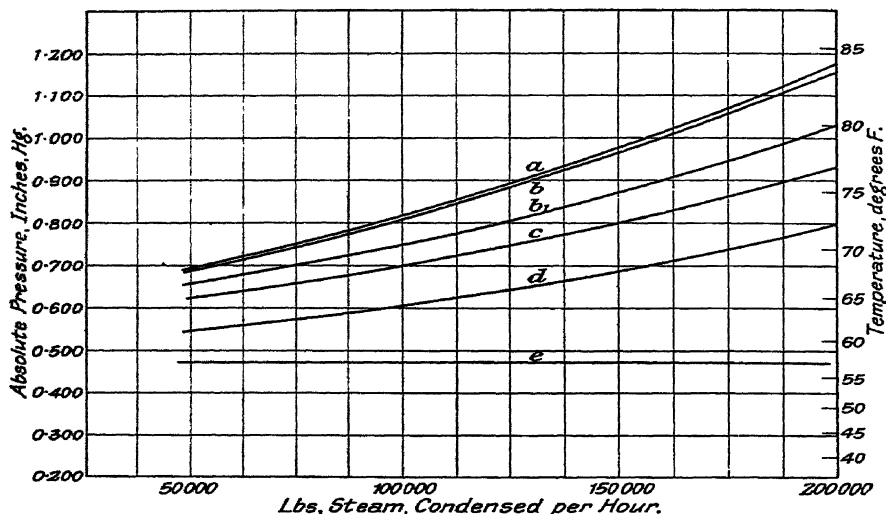


FIG. 61.—LB. STEAM CONDENSED PER HOUR.

- a* = Absolute pressure at exhaust flange by mercury column.
- b* = Absolute pressure at top of condenser by mercury column.
- b₁* = Absolute pressure at bottom of condenser by mercury column.
- c* = Condensate vapour tension corresponding to temperature.
- d* & *e* = Circulating water. Inlet and outlet tension corresponding to temperature.

Condenser Constants. There are various factors employed for expressing condenser efficiencies which are apt to confuse the junior engineer. The three expressions most commonly used are as detailed in the following—

(a) Condenser efficiency, that is, the actual quantity of circulating water required to condense a given quantity of steam, compared to the theoretical quantity.

(b) Vacuum efficiency, which means obtaining the closest temperature of condensate to the temperature corresponding to the vacuum. It is in this expression that confusion very often arises. It should be stated which temperature is taken to be the temperature of condensation, and at which point

the vacuum has been read. Sometimes the temperature at the top of the condenser is taken and sometimes the temperature of the condensate. In order to avoid any confusion the temperature of the condensate should be taken and the absolute pressure by mercury column at the bottom of the condenser. The results are directly influenced by the quantity of air present, and are an indication of the air tightness of the condenser and the performance of the air pumps.

EXAMPLE I

Temperature of condensate	70° F.
Vacuum at bottom of condenser	29.10 ins. of mercury
Barometer	30.0 " "

Then—

Absolute pressure	0.90 " "
Absolute pressure corresponding to temperature of condensate	0.739 " "
Therefore theoretical vacuum	30.0 - 0.739
	= 29.26 ins. of mercury
And vacuum efficiency	$\frac{29.1}{29.26} = 0.994$
	= 99.4%

EXAMPLE II

Temperature of condensate	70° F.
Vacuum at bottom of condenser	28.0 ins. of mercury
Barometer	30.0 " "

Then—

Absolute pressure	2.0 " "
Absolute pressure corresponding to temperature of condensate	0.739 " "
Therefore theoretical vacuum	30.0 - 0.739
	= 29.26 ins. of mercury
And vacuum efficiency	$\frac{28.0}{29.26} = 0.956$
	= 95.6%

(c) B.T.U.'s transmitted per square foot of cooling surface per hour per degree F. difference between the steam temperature and the mean of the inlet and outlet circulating water temperatures.

The foregoing statement is commonly referred to as K , and as this coefficient is directly influenced by nearly all the factors governing good condenser performance, it will be dealt with at length. Two values of K may be calculated for any

given case: (1) simple K which assumes that the actual temperature gradient along any tube follows a straight line; (2) logarithmic K which assumes each element of tube surface transmits in proportion to the actual temperature gradient. Fig. 62.

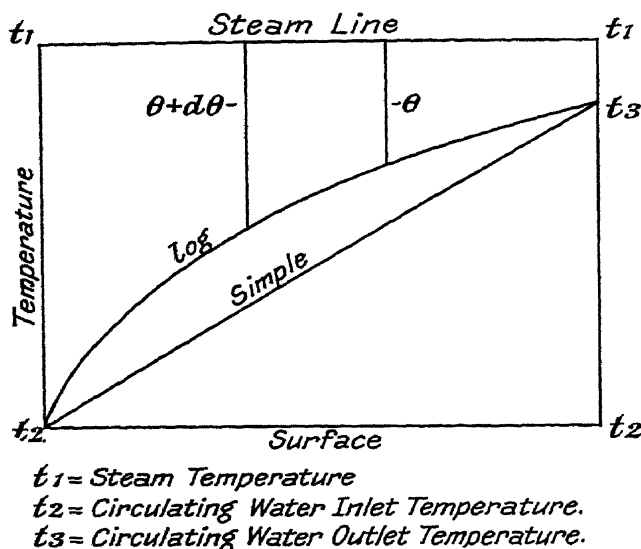


FIG. 62.

Case (1). Simple Line. From Fig. 62 the average temperature gradient $= t_1 - \frac{1}{2}(t_2 + t_3)$.

If K_s = simple K = B.T.U. per hour per sq. ft. per degree F. temperature difference.

S = surface in square feet.

W = circulating water in lbs. per hour.

$$\text{Then } W(t_3 - t_2) = K_s \left\{ t_1 - \frac{1}{2}(t_2 + t_3) \right\} S$$

$$\text{and } K_s = \frac{W}{S} \times \frac{t_3 - t_2}{t_1 - \frac{1}{2}(t_2 + t_3)}$$

Case (2). Logarithmic Line. The logarithmic formula assumes that each element of surface transmits in proportion to the actual temperature gradient.

Let θ = temperature gradient at any point. Then for an element of surface ds , if Ke equals coefficient of heat

transmission in B.T.U.'s per square foot per hour per degree F. temperature difference—

$$Ke\theta ds = W d\theta$$

$$\text{and } Keds = \frac{d\theta}{\theta} W$$

The limits of integration are from s to nothing for s and from $(t_1 - t_2)$ to $(t_1 - t_3)$ for θ .

$$\therefore \int_0^s Keds = \int_{t_1-t_2}^{t_1-t_3} W \frac{d\theta}{\theta}$$

Solution being—

$$KeS = W \log_e \frac{t_1 - t_2}{t_1 - t_3}$$

$$Ke = \frac{W}{S} \log_e \frac{t_1 - t_2}{t_1 - t_3}$$

For a given condenser. Total B.T.U. per hour

$$= (\text{B.T.U. per sq. ft. per } 1^\circ \text{ F., per hour}) \times \theta m \times S$$

θm = mean temperature difference.

Total B.T.U. per hour also equals $W(t_3 - t_2)$ and substituting the value of Ke and cancelling out we get—

$$\theta m = \frac{t_3 - t_2}{\log_e \frac{t_1 - t_2}{t_1 - t_3}}$$

$$\text{or } \theta m = \frac{0.434 (t_3 - t_2)}{\log_{10} \frac{t_1 - t_2}{t_1 - t_3}}$$

In practice the circulating water is not always easily determined and the formula is therefore difficult to apply. If the heat rejected to the circulating water, and the weight of steam condensed per square foot per hour in pounds be known, then the B.T.U.'s per square foot per hour equals $Ws \times H$,

where Ws = lbs. of steam condensed per sq. ft. of cooling surface per hour

$$= \frac{\text{lbs. steam per hour}}{\text{cooling surface}}$$

H = heat rejected to circulating water per lb. of steam

and $Ws \times H = Ke \times \theta m$

$$Ke = \frac{Ws H}{\theta m}$$

$$\therefore Ke = \frac{Ws H}{0.434 (t_3 - t_2) \log_{10} \left(\frac{t_1 - t_2}{t_1 - t_3} \right)}$$

It is impossible to fix a value for K that can be applicable in all cases, as it is influenced greatly by condenser design.

For each particular case, however, K will vary with the steam weight exhausted to the condenser, and it is quite a simple matter to draw up curves showing what are found to be the best values of K for the range of loads or steam weight handled by the turbine.

The Chloronome Treatment of Circulating Water. Where circulating water is drawn from a river or stream it is sometimes found (especially when sewage works effluent discharges into the river in the vicinity), that the condenser tubes have a tendency to become choked with an algoid growth. It has been found that the addition of a small quantity of highly chlorinated

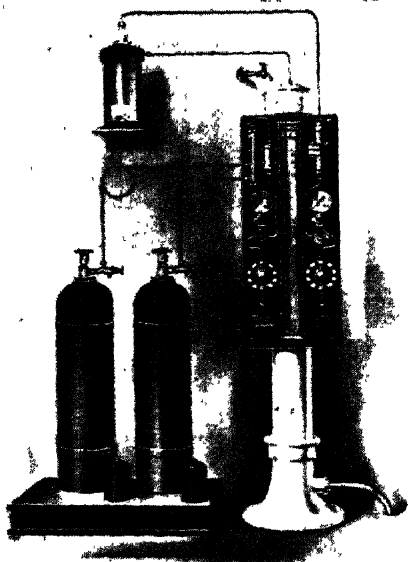


FIG. 63.—CHLORONOME APPARATUS.

water in the main supply to the condenser is sufficient to inhibit the development of the growth, and thus keep the tubes clear. Fig. 63 illustrates the Paterson "Chloronome" apparatus. Chlorine gas from the cylinders is passed through suitable reducing valves and up an absorption tower where it dissolves in water trickling down the tower, the water outlet from the base of the tower being led into the main suction pipe for the circulating water.

CHAPTER X

ELECTRICAL MEASUREMENTS

THE conventional instruments commonly used for the measurement and control of the electrical output from a turbo-alternator are: a watt-hour meter, watt-meter, power factor indicator, A.C. ammeter and volt-meter, and a D.C. ammeter and volt-meter for the exciter circuit. The accuracy and therefore the value of station operation statistics depends on the accuracy of the instruments, and as the electrical output of the station is one of the most important factors in statistical calculations, it is imperative that the watt-hour meters employed for this purpose have as small an error as possible. For test purposes, such as acceptance tests of turbo-alternators, only very carefully calibrated watt-hour meters must be employed. The instrument and transformer errors should be accurately determined and the correction curves attached to the instrument. On large 3-phase turbo-alternators, direct connected to step-up transformers, it is customary to measure the alternator output by a watt-hour meter on each phase, and also by the two watt-hour meter method during tests. By doing so the power factor of the alternator and also the efficiency of the step-up transformers can be determined.

Alternator Cooling. The majority of modern turbine-driven alternators are artificially cooled, and it is necessary that some provision should be made for readily ascertaining the nature and temperature of the cooling air entering and leaving the alternator. For temperature measurements thermocouples are readily adaptable, and the leads from the couples can be taken to a common thermocouple plug-board and indicator panel as shown in Fig. 49.

There are several methods of measuring the rate of flow of cooling air supplied to an artificially cooled alternator. These are—

- (a) Calibrated orifice.
- (b) Pitot tube.
- (c) Anemometer.
- (d) Electrical method. (Thomas air meter.)

Owing to the size of the air-ducts and the difficulty of obtaining uniform velocity of the air, the first three methods mentioned do not give satisfactory results. The electrical method consists in measuring the quantity of heat necessary to raise the temperature of the air by a given amount, from which the rate of flow can be calculated. By a slight rearrangement of the apparatus it is also possible to determine the total losses in a loaded alternator with considerable accuracy. The air meter and necessary instruments are of a portable nature, the former consisting of a chimney built up of wood and fuller board which can be placed on the air outlet on top of the alternator.

Motor-driven Auxiliaries. The measurement of the power taken by the electrically-driven auxiliaries is very often neglected, but the provision of measuring and indicating instruments on the auxiliary circuits should enable the operating engineer to maintain the power consumption for station service at a minimum.

Turbo-alternator Measuring Instruments. The question as to the minimum of instruments which are necessary cannot be answered fully here. Many stations with only a few instruments can show points in efficient operation to stations where money has been lavishly expended on the purchase of apparatus for scientific efficiency control. The maintenance of high efficiency requires regular and exacting supervision and inspection, and if the operating engineer is to have complete control of the factors influencing efficient turbine-room performance, he must have : (1) means for readily ascertaining when changes in conditions are taking place ; (2) he must know what each unit of plant can do and the combinations of conditions which will produce the best results. The first mentioned can only be remedied by the provision of instruments which continually indicate or record—

- (a) The input to each turbine.
- (b) The electrical output of each alternator.
- (c) Condenser conditions.
- (d) Power consumption of auxiliary machinery.

A selection of the principal test points on a turbo-alternator unit are shown in Fig. 64 (A) and (B).

The knowledge referred to under heading (2) can only be arrived at by extensive test and research work, and in the larger undertakings such work is now in the hands of a tests

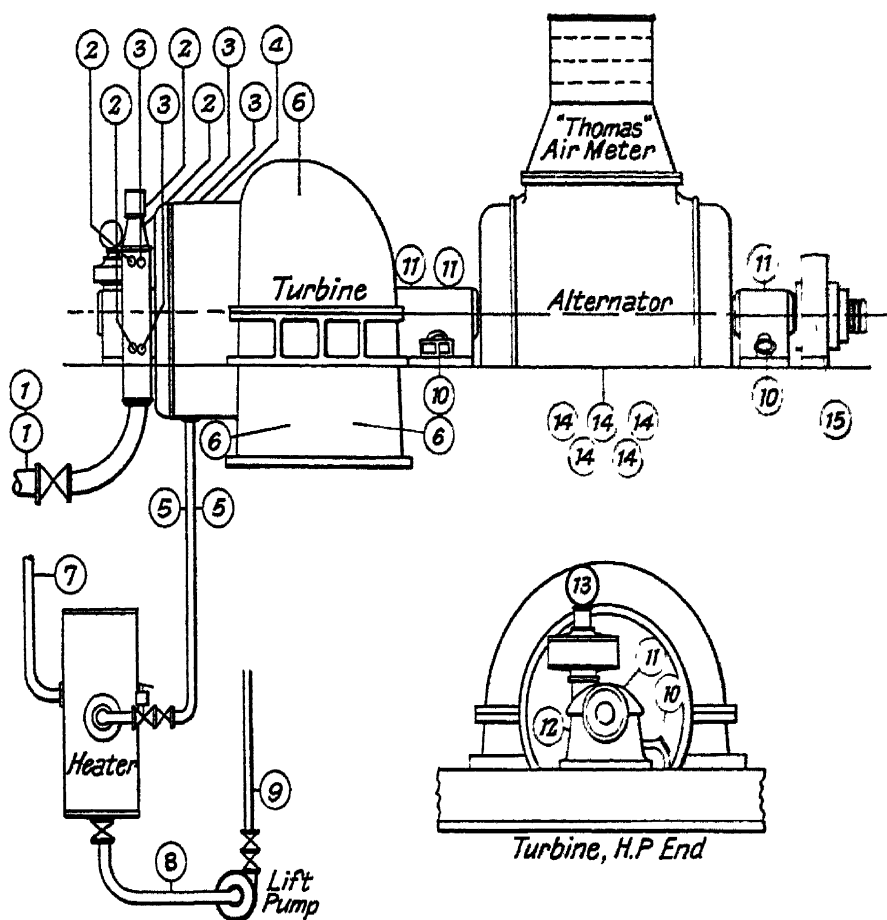


FIG. 64 (A).

1. Stop valve steam pressure and temperature.
2. Governor valve steam pressures.
3. Governor valve steam temperatures.
4. Steam pressure after first expansion.
5. Bled steam pressure and temperature.
6. Exhaust steam temperature.
7. Temperature of condensate from test tanks or other measuring gear.
8. Temperature of condensate leaving heater.
9. Temperature of condensate to hot-walls.
10. Bearing oil temperatures.
11. Bearing oil pressures.
12. Governor relay oil pressure.
13. Turbine speed.
14. Alternator instruments, load output, etc.
15. Exciter instruments.

department, under the control of a man specializing in the investigation of all problems affecting economical generation, the duty of the operating engineers being to maintain the

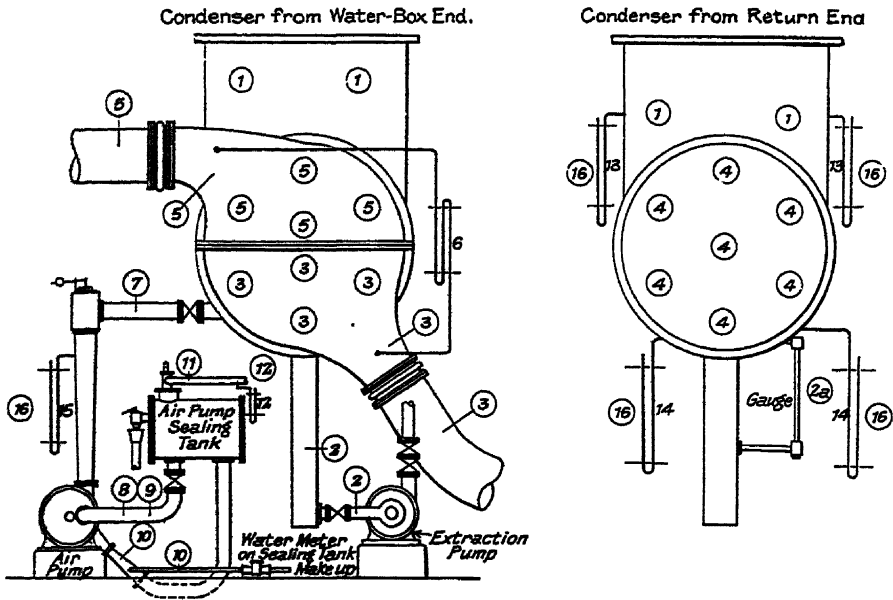


FIG. 64 (B).

1. Exhaust steam temperatures.
2. Condensate temperatures.
3. Circulating water inlet temperatures.
4. Circulating water temperatures at return water box
5. Circulating water outlet temperatures.
6. Circulating water friction drop, inches of mercury.
7. Temperature of air leaving condenser.
8. Temperature of sealing water to air pump.
9. Pressure of sealing water to air pump.
10. Temperature of discharge from air pump and make-up.
11. Temperature of air leaving sealing tank.
12. Orifice plate, U-tube, and thermometers for measurement of air quantity.
13. Vacuum at top of condenser.
14. Vacuum at bottom of condenser.
15. Vacuum at air pump inlet.
16. Temperature of mercury columns.

prescribed conditions. If all requirements specified by the tests department are complied with, the best results inevitably follow. The human element is the great factor influencing the results of any station, but given intelligent operation and competent maintenance the results obtained should approximate very closely to the best possible.

CHAPTER XI

AUXILIARIES AND HEAT BALANCE CONTROL

IN most of the modern large power stations there are usually three or four sources for the supply of auxiliary energy, which are governed by various combinations of plant.

Depending upon the combination of station plant supplying the commercial load, the problem of generating this energy for operating the station auxiliaries and of simultaneously utilizing the heat energy rejected, is one of the greatest problems of heat balance and power station economy.

Enough energy must be developed to perform the work required of the station auxiliaries and this energy must be developed by steam, in such a manner, that either all the available energy in the steam is extracted, or that part of it is utilized in the production of auxiliary power and the remainder returned in a lower form to the main heat stream of the station.

In other words, the useful energy in the steam above the temperature to which it is desired to heat the feed-water must be extracted, and the steam flow must be easily controlled, so that no more heat is available than is required.

Reliability. In certain cases efficient heat balancing is of secondary importance to reliability of service, and the operation of auxiliary plant is then of a straightforward and simple nature. Where heat balancing is employed the most efficient combinations of plant to carry the various loads, and at the same time supply the energy for station auxiliary services, can only be determined by a long series of investigations and the recording and tabulation of all station data. Once, however, the various combinations have been worked out it is then a simple matter for the engineer-in-charge to operate his plant according to this schedule. The methods by which the various combinations of plant are determined are too lengthy and complicated to detail in full, and only a consideration of the general methods of driving auxiliary plant and their effect on station operation can be considered here.

Methods of Driving Auxiliaries. Broadly speaking, there are three general methods available of supplying auxiliary power and at the same time controlling the heat balance.

These are: (1) all steam drive of auxiliaries with exhaust steam for feed heating; (2) all electric drive with energy supplied from the station main bus-bars, in conjunction with steam bled from a stage of the main turbines for feed-water heating; (3) all electric drive with energy for auxiliary purposes supplied from one or more house-turbines, the exhaust steam from the house-sets being utilized for heating the feed-water. In general, with electrical supply for the operation of auxiliaries generated either by the main units or an auxiliary source, the use of main unit energy without bled steam for feed heating, is "steam efficient," and the use of an auxiliary source with feed-water heating is "heat efficient."

There are, of course, other systems of supplying auxiliary energy employing combinations of the three methods of heat balance control, given above, and it is in such cases that the determination of the most efficient combinations of plant becomes a difficult problem.

All Steam Drive. Referring to the systems just mentioned the first is the oldest, and it was considered good practice some time ago to have all the auxiliaries of one of the main units steam-driven, facilitating heat balance control, and for reliability during abnormal conditions and disturbance in continuity of service. The small impulse steam turbine was the unit usually adopted for these individual drives, with a steam consumption in the neighbourhood of 35 to 40 lbs. per kilowatt-hour.

This meant that if the exhaust steam from these small turbines was to be effectively utilized, a complication of exhaust piping ensued that compares unfavourably to the more readily adaptable house turbine system.

Due to the high degree of superheat now carried, the use of this exhaust steam, containing often as much as 100° F. of superheat, is limited, owing to the fact that it imposes temperature stresses on the material and limits the heat transfer of closed feed-water heaters. Further, this type of drive does not allow a very accurate control of feed-water temperature, as the auxiliary machinery has to be distributed throughout the plant where required. It is thus very inflexible in the regulation of the heat balance. The use of separate steam-driven auxiliaries also complicates the steam-piping and increases the percentage of make-up water required, owing to the greater sources for thermal losses.

All Electric Drive. The supply of energy for auxiliary

purposes from the station main bus-bars lends itself to all station power disturbances, and since it is essential that every precaution be taken to ensure continuity of at least the station service, the adoption of this method means that the time is increased to re-establish the supply when it is interrupted through fault conditions. Where steam is bled from the main turbines for feed-water heating, and where heat economy is of first importance, this method of auxiliary driving is the only choice. The cost in heat units of energy for auxiliary driving, derived from the main alternators is, in a modern plant, from 13,000 to 16,000 B.T.U.'s per kilowatt-hour.

If a house turbine is used for supplying the auxiliary power, and assuming that all the heat in the exhaust steam can be efficiently utilized for feed-water heating, the heat cost of auxiliary energy will be reduced to a value in the neighbourhood of 4,000 to 5,000 B.T.U.'s per kilowatt-hour.

If sufficient steam be bled from the main units at a stage to give the necessary temperature to the feed-water, and if this bled steam covers the percentage of auxiliary power required, it will be seen that the heat cost of auxiliary energy can still be kept to the figure mentioned, and the heat balance efficiently controlled.

One firm of turbine manufacturers build a bled steam feed-water heater integral with the turbine, while in other cases the bled steam is led to a separate heater. The diagrammatic arrangement of the integral feed-water heater of a bled steam turbine, and the distribution of the heat units at full load, is shown in Fig. 65. The use of a house turbine for heat balancing and generating the auxiliary energy is representative of modern practice in America and to a small extent also in this country. The house turbine is a small turbo-generator unit of sufficient capacity to supply all, or a certain proportion of, the auxiliary plant (Fig. 66). Owing to its larger size, compared with the small steam turbine for individual drive, it is possible to utilize more efficient staging, the steam consumption of these house turbo sets being usually in the neighbourhood of 20 to 25 lbs. per kilowatt-hour. The steam per kilowatt-hour cost is, therefore, half that of the small auxiliary turbine. The exhaust of the house turbine is utilized to heat the feed-water by means of a type of condenser heater, something similar to a jet condenser.

While the house turbine system provides a high factor of reliability by maintaining part or all of the auxiliary services

during times of disturbance to the continuity of the main supply, it has a low thermal efficiency, and its limits in this direction are now recognized.

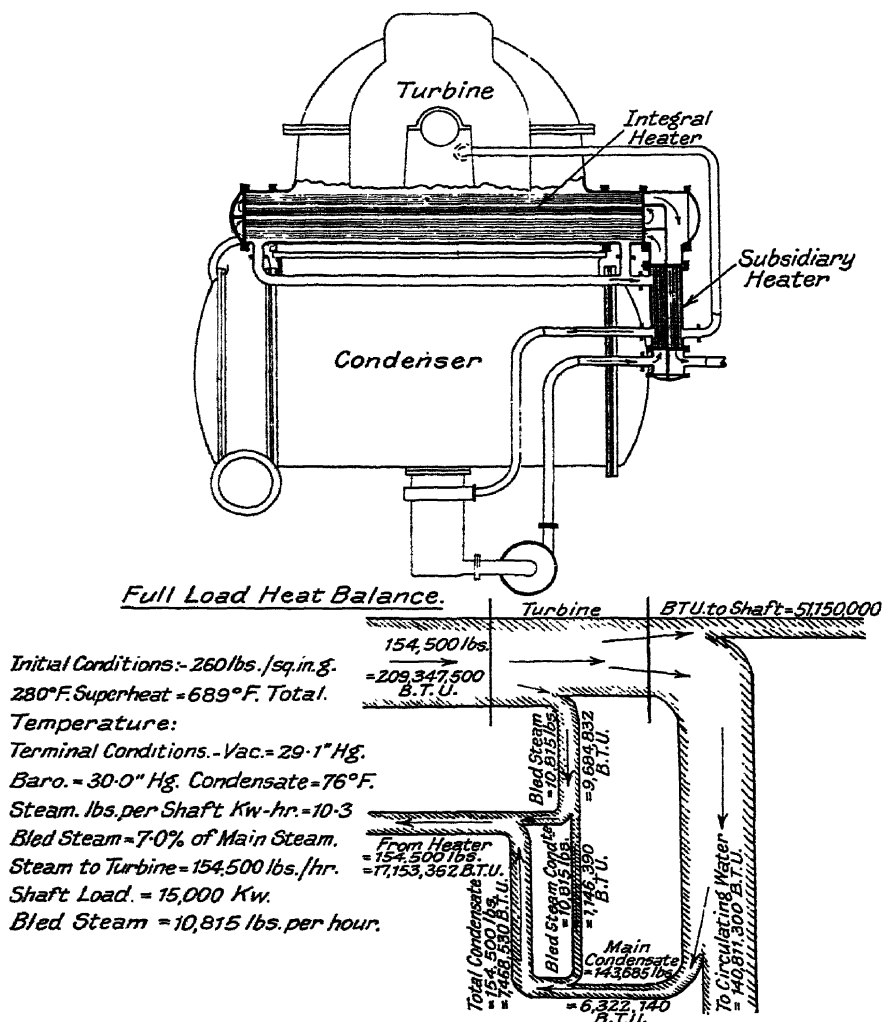


FIG. 65.—ARRANGEMENT OF BLED STEAM FEED-WATER HEATER.

Amongst recent proposals for the supply of auxiliary energy is the adoption of a small generator on the main turbo-alternator spindle. In the case of all auxiliary service being supplied from such a source, it means that in the event of a complete failure the auxiliary service has to be re-established

by running up the main turbine on atmosphere. This practice should not be encouraged, as it subjects the turbine and condenser to wide variations of temperature in a short space of time. While on this subject, it should be pointed out to the operating engineers that in the event of a failure of auxiliary supply resulting in a turbine "going over" to atmosphere, the load must be removed from the unit immediately. An instance of such a case was given recently in the report of a

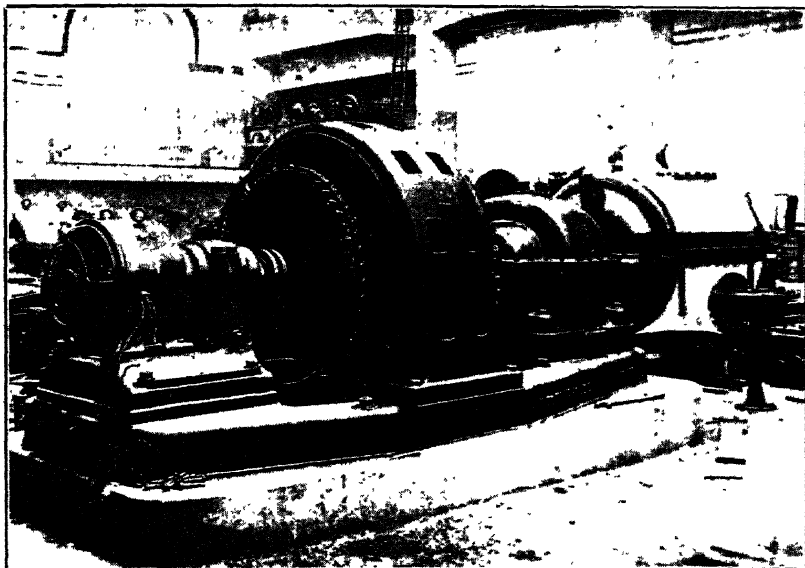


FIG. 66.—500 KW. HOUSE TURBINE.
(In course of erection)

British insurance company. In this case, the vacuum failed due to a loss of circulating water, the temperature at the exhaust end of the turbine rising from 90° F. to over 300° F. This resulted in the distortion of the nozzles on the last stage, the amount of distortion being sufficient to bring the diaphragm and nozzles into contact with the last wheel of the rotor.

Another method of supplying energy for electrically-driven auxiliaries, and which at present is receiving a certain amount of favour, is from a small step-down transformer connected direct to the outgoing leads of the main alternator. Such a system makes a complete unit of the turbo-alternator and its auxiliary plant, but in cases where the main field of the alternator is arranged to "break" with the main oil switch of the

unit, the auxiliaries are again liable to failure from disturbances outside the station.

An interesting proposal recently put forward for the supply of auxiliary energy and heat-balancing is the use of the highly thermally-efficient internal combustion engine driving a generator for station service, the exhaust gases from the engine being utilized to heat the feed water.

Feed-water Temperature Regulation. The control of house turbine load provides a sensitive means of regulating the feed-water temperature. Various methods have been used as the basis of this control. If the characteristics of the generator permit, it can be synchronized through transformers with the main sets and the temperature of the feed-water regulated by an exchange of load. This method, of course, means that the power for the auxiliaries is liable to disturbance from sources outside the station, thus introducing the bad feature inherent to auxiliary drive by power derived from the station main bus-bars. Several methods of overcoming this difficulty to a certain extent are in use. A synchronous generator, driven by an induction motor supplied from the main bus-bars, carries the variations in auxiliary load necessary to regulate the feed-water temperature. The load can be shifted from motor generator to house turbine or vice versa by slightly altering the frequency of the latter. The control of the feed-water temperature can thus be centralized, the necessary alterations being made by the operating engineer.

In one instance not only is this control centralized, but also all the auxiliary controls, the whole being grouped on one control board and in charge of a skilled operator.

Records of the daily operation show that for days at a time the boiler-room hot-well temperature never varied more than one or two degrees from 210° F., being controlled entirely by the house turbine governor control. Tests showed that the house turbine load could be varied in steps of 10 kilowatts, the feed-water temperature being regulated to within 0.5° F.

CHAPTER XII

A MODERN EXAMPLE OF HEAT BALANCE CONTROL

AN example of a modern power station equipped with a combination of systems for supplying auxiliary energy and controlling the heat balance is the Dalmarnock Station of the Glasgow Corporation Electricity Department. In this case heat balance control can be effected by three distinct systems. Two house turbines are provided, each of 500 kilowatts capacity, exhausting into open type feed-water heaters. Two of the main units are arranged with integral bled steam feed-water heaters, whilst other two main units are also arranged for steam bleeding in conjunction with open type feed-water heaters. All auxiliaries are electrically-driven with the exception of boiler feed-pumps and the steam-jet condenser air ejectors of two of the main units, the exhaust from the ejectors discharges into a feed-water heater. Duplication of auxiliaries is provided in the case of the main unit condensate and air extraction pumps, and electrically-driven boiler feed-pumps duplicate those which are steam-driven. The electrically-driven auxiliaries can be supplied from the house turbines, unit transformers, house transformers, or low tension tertiary windings on the legs of the main step-up transformers. The whole auxiliary and heat balance system at first seems complicated, but the conditions provide for maximum heat economy and simultaneously assure a high factor of reliability. The best basis so far found for normal operation is steam bled from the main turbines at a stage corresponding to an absolute pressure in the neighbourhood of 8 ins. of mercury, and passing this through a feed-water heater integral with the turbine. The point of importance in this is that the loss to the condenser has been tapped for feed-water heating.

Records and Statistics. Of the greatest importance in obtaining maximum heat economy is the efficient recording and tabulation of operating data. In any power station a daily log-sheet system should be in operation for each section of the station, viz. boiler-house, turbine-room, and control-room.

To summarize what has been said concerning the boiler-house. Each boiler should be provided with its own control board carrying the instruments for indicating or recording

steam pressure, steam temperature, steam flow, temperature of flue gases at inlet and outlet to economizer, air temperature, CO² percentage, and temperature of the feed-water entering and leaving the economizer. The plant should be entirely operated from the indications of the instruments, and the indications entered in the log sheet at, at least, half-hourly intervals. The coal being fed to the boilers must be metered as accurately as possible by some form of automatic weighing machine, so that the coal consumption over any period is known. Samples of the coal being fed to the boiler furnaces should be taken at frequent intervals in a systematic manner, and at the end of the day or other predetermined period, a representative quantity should be selected from the sample by one of the methods previously described, and tested for moisture, volatile matter, fixed carbon, ash, and calorific value. In the turbine-room each turbine with its condenser should be supplied with the necessary instruments for indicating or recording the initial and terminal conditions. The turbine plant should be operated from the instrument indications, readings of which should be taken and entered in the turbine-room log-sheet at, at least, half-hourly intervals. Preferably, the condensate from each turbine should be metered. In the cases of closed feed systems the steam to the turbine should be measured, the condensate metered by a Venturi tube, or the pressures logged, and the consumption calculated from steam conditions and nozzle areas as described. If the make-up feed-water is also metered, the boiler-house evaporation and the steam consumption of the turbine room can be separately determined. The turbine-room log-sheet must supply all the information necessary for keeping a continuous check on the steam consumption and overall turbine-room performance in general. The following is an example of the data required for each turbine for this purpose.

Though this example is more representative of the data required for test purposes or special investigation work than that necessary under everyday operating conditions, it should be borne in mind that the more comprehensive the log sheet, without being too prolix, the better will be the facilities for keeping a continual check on the factors influencing efficient operation.

Load in kilowatts on each turbine.

Condensate or steam	.	.	.	.	Rate of flow per hour
Steam pressure at stop valve	.	.	.	.	lbs. per □" g.

Steam temperature at stop valve	. .	deg. F.
First governor valve steam pressure	. .	lbs. per \square " g.
Second governor valve steam pressure	. .	lbs. per \square " g.
Third governor valve steam pressure	. .	lbs. per \square " g.
Fourth governor valve steam pressure	. .	lbs. per \square " g.
First expansion steam pressure	. .	lbs. per \square " g.
Exhaust steam temperature	. .	deg. F.
Standard barometer	. .	inches of mercury
Vacuum at top of condenser	. .	inches of mercury
Vacuum at bottom of condenser	. .	inches of mercury
Vacuum at top of condenser :		
referred to baro. of 30.00 ins. of mercury		
Vacuum at bottom of condenser :		
referred to baro. of 30.00 ins. of mercury		
Condensate temperature leaving condenser	deg. F.	
Condensate temperature leaving first heater	deg. F.	
Condensate temperature leaving second heater	deg. F.	
Circulating water inlet temperature	deg. F.	
Circulating water outlet temperature	deg. F.	
Bearing and governor oil temperatures and pressures.		
Power taken by auxiliaries.		

At the end of the day, or other period, the values of each column of the log-sheet should be averaged in a somewhat similar manner to that in which the averages are taken out for the boiler-house daily operation statistics and which was described in an earlier section of the book. From the values obtained the principal turbine-room data can then be calculated. This should include—

General—

- Hours run of each turbine.
- Electrical output of each turbine.
- Total electrical output of station.
- Power consumption, boiler-house auxiliaries.
- Power consumption, turbine-room auxiliaries.
- Power consumption, coal-handling plant.
- Station lighting and subsidiary services.
- Total power consumption of station.
- Total electrical output to feeders.
- Steam, in pounds, taken by each turbine.
- Total turbine-room steam, in pounds.
- Make-up water, in pounds.
- Total station steam, in pounds.
- Steam consumption of turbine-room per kw.-hr. generated.
- Steam consumption of station per kw.-hr. generated.
- Steam consumption of station per kw.-hr. delivered.
- Turbine-room thermal efficiency.

For each turbine—

Steam consumption	lbs. per kw.-hr.
Averages of initial conditions.	
Averages of terminal conditions.	
Total absolute pressure, bottom of condenser	inches mercury
Vapour tension corresponding to temperature of condensate	inches mercury
Air tension, bottom of condenser	inches mercury
Turbine efficiency ratio.	

Preferably, the principal values enumerated above should be determined at the end of each shift, so that inefficiencies can be investigated before it is too late.

The station electrical records should be confined to the one sheet and kept entirely separate from the turbine-room and boiler-room figures. For statistical purposes it is necessary to know the output of each alternator and the total station output for any period. The power consumption of the auxiliaries should also be known and preferably apportioned against the sections of the station where consumed. That is to say, the consumption of turbine-room and boiler-room auxiliaries, coal-handling plant, etc., should be determined separately.

To Obtain the Heat Balance. It ought to be possible if all the foregoing data is properly tabulated to ascertain the heat balance of any part of the station equipment, and also the heat balance over the station for any period. The analysis of heat balance statements is of the greatest value in the determination of the most efficient methods of plant operation, and a comprehensive log-sheet system is of the first importance if these analyses are to be easily made. The following (Table XVII) is an example of a heat balance statement for a modern power station, showing practically at a glance the distribution of the heat units or their equivalents throughout the whole station. This heat balance statement does not represent the best that has or can be obtained for the plant in question, the calculations being made from actual figures obtained under everyday operating conditions in 1921, with a load factor of 41.6 per cent and the following plant in commission: seven boilers, one 18,750 kilowatt bleed steam turbo-alternator, one 18,750 kilowatt turbo-alternator with steam jet ejectors for condenser air extraction, one steam-driven boiler feed-pump, and all other auxiliaries electrically-driven.

TABLE XVIIa

HEAT-BALANCE STATEMENT—DALMARNOCK POWER STATION

	Lbs.	B.T.U.'s.
Total Coal per Hour	39,732	429,105,600
Steam Produced per Hour	261,040	355,536,480
" to No. 2 Main Unit	114,500	154,804,000
" " No. 2 " " " "	136,500	184,548,000
" " Boiler Feed Pump	2,215	3,016,830
Loss, Blow-down, Traps, Glands, Lea Over- flow, and Unaccounted for	7,825	13,167,650
Total	261,040	355,536,480
Total Heat in Feed-water		28,453,360
Net Heat Added in Boiler		327,083,120
<i>Main Unit Input—</i>		
Steam to No. 1 Turbine and Ejectors	114,500	154,804,000
" " No. 2 " " " "	136,500	184,548,000
	251,000	Total 339,352,000
<i>Main Unit Output—</i>		
No. 1 Main Unit	11,041 kw.-hrs.	37,649,810
No. 2 " " " " " "	2,145 "	41,414,450
No. 1 Condensate	110,000 lbs.	3,004,460
No. 2 " " " " " "	125,300 "	4,009,600
Heat Rejected in Circulating Water No. 1		103,907,600
" " " " " " No. 2		116,027,800
Losses in "No. 1" Main Unit		10,242,130
"Bled" Steam and Losses in No. 2 Main Unit		3,096,150
	Total	339,352,000
<i>Available for Feed-water Heating—</i>		
From No. 1 Ejectors	4,500 lbs.	5,044,500
" Bled Steam No. 2 Main Unit	11,200 "	12,558,000
" Boiler Feed Pump	2,200 "	2,290,900
	Total	19,893,400

TABLE XVIIb

HEAT-BALANCE STATEMENT—DALMARNOCK

<i>Heat to Condensate—</i>	Lbs.	B.T.U.'s.
No. 1 Condensate	110,000	3,004,460
Ejector Steam and Gain in Heater	4,500	5,044,500
No. 2 Condensate	125,300	4,009,600
Heat Gain in "Bleeder"		12,558,000
"Bleeder" Condensate	11,200	1,326,800
Make-up Water	7,825	219,100
Exhaust from Boiler Feed Pump	2,215	2,290,900
Total to Boilers	261,040	28,453,360

Overall Efficiency. A good system of recording the daily overall performance of the different sections of the station is in the form of graphs. These show at a glance the trend of the various efficiencies, any falling off being at once detected and investigations made. The three principal efficiencies are : boiler-house, turbine-room, and overall. The two first have already been discussed. The overall thermal efficiency represents the percentage of heat units appearing in the form of electrical energy at the station bus-bars, derived from the combustion of unit weight of the coal, or in other words, it is the relation between the B.T.U. equivalent of the kilowatt-hour and the B.T.U.'s liberated from the coal required to produce one kilowatt-hour.

The value expressed as a percentage can be obtained from the following formula—

$$\frac{3414}{nC} \times 100$$

where n = lbs. of coal consumed per kilowatt-hour generated.

C = calorific value of the coal as fired, in B.T.U.'s per lb.

An example of these three efficiencies tabulated in graphical form is shown in Fig. 67. Besides recording these values in graphical form, the principal turbine figures should be kept in this manner also, as shown in Fig. 68. The chief items requiring continual supervision on each turbine are the steam consumption and the terminal conditions. These are shown plotted in Fig. 68, and are from values obtained in actual practice.

Power Station Cost Accounting. The subject of power station cost accounting is primarily of interest to those executives who are interested in power station practice only indirectly, and purely from a profit and loss point of view. The average power station engineer, though perhaps fully familiar with every phase of power station operation, seldom gives very much attention to the systematic recording of station costs. Power station cost accounting, to be a success, demands a close co-operation of the operating, technical, and clerical staffs. An efficient system of cost accounting helps considerably towards lowering the cost of generation, because it supplies a much needed link between departments which in the past have been too self-centred. This does not mean that the power station engineer must necessarily be an expert

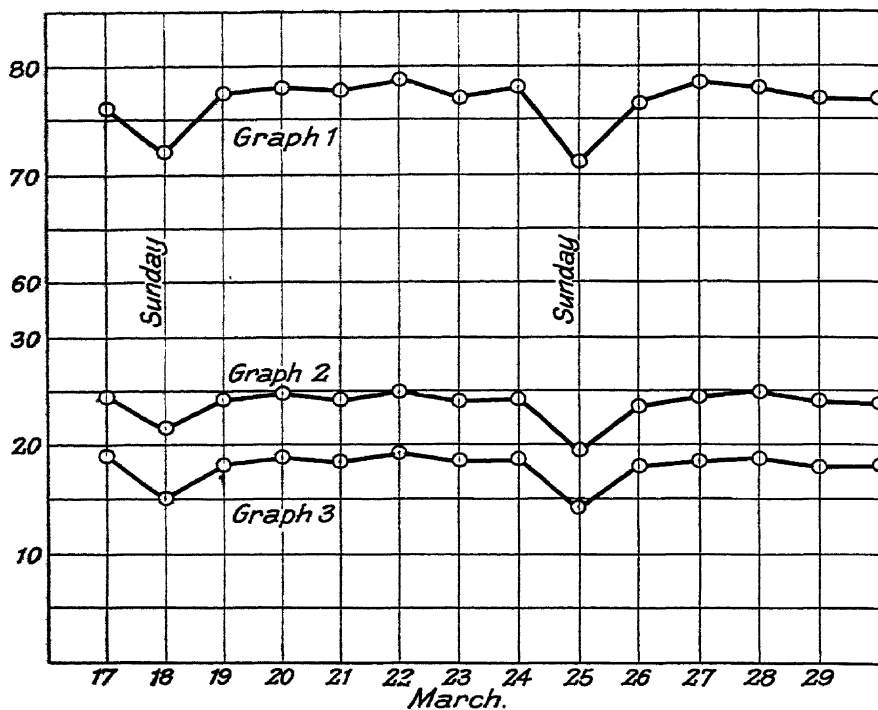


FIG. 67.

Curve 1 : Boiler-house efficiency. Curve 2 : Turbine-room efficiency.
Curve 3 : Station overall efficiency.

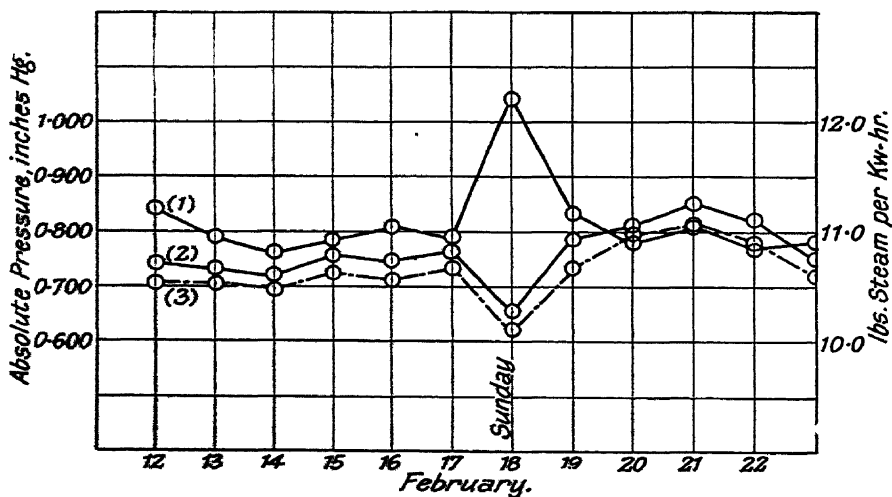


FIG. 68.—TURBINE NO.

Curve 1 : Steam consumption, lbs. kw.-hr.
Curve 2 : Actual absolute pressure at bottom of condenser.
Curve 3 : Absolute pressure corresponding to temperature of condensate.

in accountancy methods, but he should at least be familiar with that part of the system involving station generation costs. After all is said the figure of merit for any power station is the cost in money to produce a kilowatt-hour to the feeders. The station log-sheets, besides forming the basis for the tabulation of technical statistics, should also be the basis of the station generation costing system. The log-sheet methods outlined in this book supply the information necessary for the compilation of station weekly statistics, and the station operating engineer should be familiar with the figures for his plant right up to this point. Table XVIII, shown on p. 221, is an example of a weekly generation statistics sheet.

Efficiency Charts. As a further aid towards maintaining efficiency and a check on operating results, a system should be instituted such as that devised by Mr. R. H. Parsons. This system is fully explained in the "Coal Consumption of Power Plants," published by the *Electrical Review*. The author has been closely associated with the adoption, institution, and operation of this system in the power stations of the Glasgow Corporation Electricity Department, and recommends it to the keen engineer desirous of improving his station performance. Briefly, it is a method by which standard coal and water consumption for the stations are arrived at, and the operating results of the power station considered as a unit can be analysed.

In putting into operation such a system, charts are drawn up in which the coal consumption and total water evaporated are plotted against the corresponding electrical outputs. The points thus obtained will be found to lie about a straight line. These straight lines represent the average performance of the station over the period for which the observations have been made, and the equations obtained from the lines provide information of great importance in the operating of the plant. It may be argued that uncertainty as to the correct position of the lines through the points would render such information inaccurate. Nevertheless, there are simple means of checking their accuracy.

Deductions from the Charts. Fig. 69 shows the line obtained by plotting the coal consumption against a base of kilowatt-hours generated.

Fig. 70 is the line obtained by plotting total water evaporated on a similar base. The range of output dealt with is seen

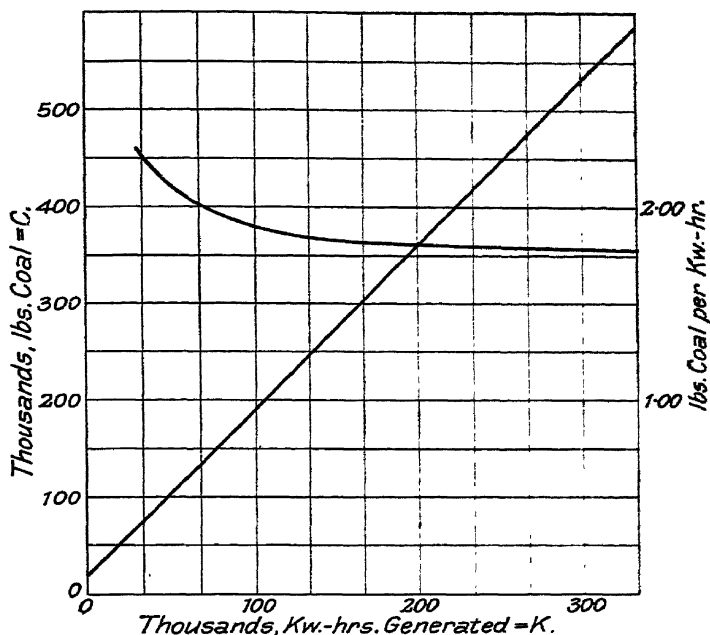


FIG. 69.—COAL PER SHIFT LINE FOR ONE MONTH'S OPERATION.

Equation for line: $C = 20,000 + 1.695 k$. Curve: Coal per kw.-hr.

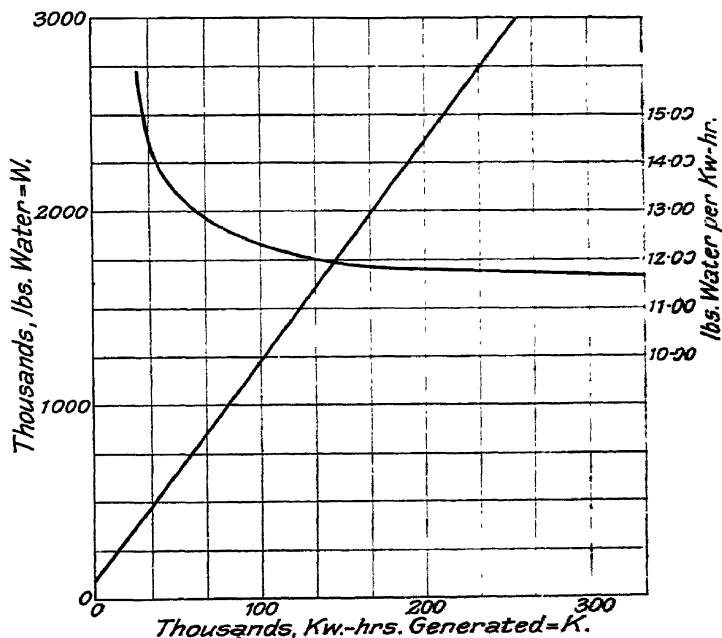


FIG. 70.—WATER PER SHIFT LINE FOR ONE MONTH'S OPERATION.

Equation for line: $W = 100,000 + 11.3 k$. Curve: Water per kw.-hr.

immediately from the graphs. From Fig. 69 the following equation is deduced—

$$C = 20,000 + 1.695 K \quad . \quad . \quad . \quad . \quad (1)$$

where C = lbs. of coal consumed per shift.

and K = electrical output in kilowatt-hours per shift.

The curve on the same graph-field shows the pounds of coal per kilowatt-hour. The principal deductions from the equations obtained are : the no load coal consumption is 20,000 lbs. of coal per shift, and the minimum coal consumption is approximately 1.77 lbs. per kilowatt-hour.

The graph in Fig. 70 deals in a similar way with the relationship between the water evaporated and the electrical output, the equation deduced from the line is—

$$W = 100,000 + 11.30 K. \quad . \quad . \quad . \quad . \quad (2)$$

From this it is seen that the no load steam consumption is in the neighbourhood of 100,000 lbs. per shift, and the minimum water rate is 11.60 lbs. per kilowatt-hour.

Eliminating K from these equations we get—

$$C = 5,000 + 0.15 W. \quad . \quad . \quad . \quad . \quad (3)$$

$$W = 6.90 C - 33,300 \quad . \quad . \quad . \quad . \quad (4)$$

From the former it is seen that the coal consumption per shift would be 5,000 lbs. if no water were to be evaporated, but normal temperature and pressure conditions maintained. In other words, it is the radiation loss in the boiler-rooms. The latter equation shows that the maximum evaporation per pound of coal is 6.90 lbs. of water, and assuming that the coal was of 10,500 B.T.U.'s per pound, and knowing the conditions of steam pressure and temperature and feed-water inlet temperature, the limiting efficiency of the boiler-house is approximately 80 per cent.

Equations (3) and (4) can also be used as a check on the accuracy of the first two. If another graph is prepared in which coal consumed is plotted against water evaporated, the equation obtained for the line ought to be the same as that obtained by eliminating K in the first two equations. An example of this line is the graph in Fig. 71, which shows graphically equations (3) and (4).

A further interesting deduction from the first and third

equations is that the difference between 20,000 and 5,000, i.e. 15,000 lbs. of coal represents the heat lost on the engine-room side of the stop-valve.

For the purpose of bringing clearly to the operating engineer's attention any progressive increase or decrease of station efficiency, a further graph of simple construction is used.

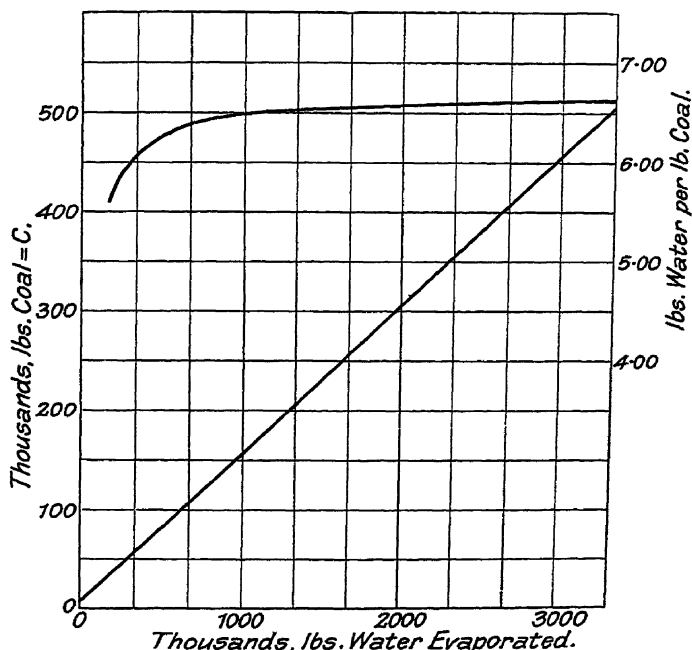


FIG. 71.—EVAPORATION LINE FOR ONE MONTH'S OPERATION.

Thousands lbs. water evaporated. Equation for line: $C = 5,000 + 0.15 w$.
Curve: Water evaporated per lb. coal.

Referring again to equation (1) it is seen that if there were no constant term the coal consumption would be 1.695 for all outputs. Therefore when the operating results come in at the end of a shift, if the engineer first subtracts the constant from the actual consumption and then divides the remainder by the electrical output, he will, if the standard of efficiency has been maintained, get 1.695. An example of such a chart is shown in Fig. 72. A heavy straight datum line is drawn along the value 1.695 and the operating results plotted on, above or below, as the case may be. A similar method can be used to obtain a continuous graphic record of the station water rate.

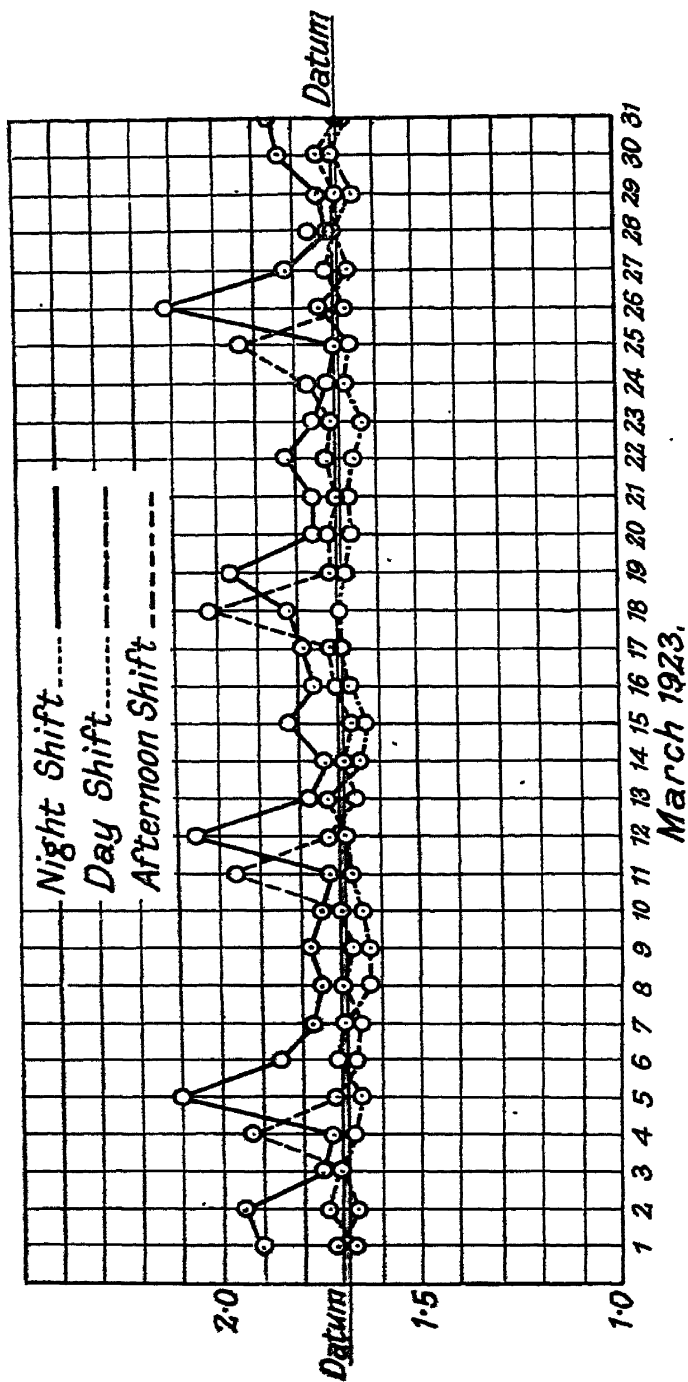


FIG. 72.—DAILY RECORD OF COMPARATIVE EFFICIENCY,

BASED ON COAL LINE FOR FEBRUARY, 1923.

Equations from coal line for February: $C = 20,000$ and $1.695 k$.

$$\text{March datum: } 1.695 = \frac{C - 20,000}{K}.$$

A point of great importance in the successful application of this system of checking the shift to shift operating efficiency, is that all coal meters, water meters, and electrical meters must, at the end of each shift or other period, be read simultaneously. If this point is neglected the time error introduced makes the results useless for comparative purposes.

APPENDIX

THE ANALYSIS OF POWER STATION RECORDS

By R. H. PARSONS, M.I.Mech.E., M.E.I.C., Assoc.M.Inst.C.E.

The Importance of Records. The first step towards the reduction of coal consumption in a power station is to know exactly what the coal consumption amounts to per unit of power turned out, as otherwise there is no certain means of ascertaining the benefit or otherwise of any alteration, whether voluntary or unintentional in the conditions of operation. It is obvious, furthermore, that this knowledge must be available at comparatively frequent intervals of time, so that inefficiency may be detected at the earliest moment and steps taken to remedy matters without delay. In an ordinary power station the natural periods over which records should be taken are the three eight-hour shifts into which the day is divided, as not only are the intervals convenient ones but each coincides with the operation of the plant by a particular group of men.

The Difficulties of Comparison. Records, by themselves, are, however, a mere waste of time unless some intelligent use is made of them. A direct comparison between the operating results of different shifts is very misleading, for, as every station engineer knows the efficiency of the plant during any particular shift will depend enormously on the load during that shift. This point is so important that it may be illustrated by an actual case. A plant turning out 45,000 kw.h. on the day shift consumed only 1.94 lbs. of coal per kw.h. on that shift, although the same plant could not carry the night shift output of 5,000 kw.h. with a coal consumption of less than 5.26 lbs. per kw.h. It would be admittedly impossible for the men on the night shift to reduce their coal consumption to the figures obtained on the day shift, yet no power-house superintendent could tell by looking at the above figures which result was the most creditable. Nevertheless there must be found some way of comparing the results if an effective check upon the efficiency of operation is to be maintained.

A Simple Solution. The method about to be described permits the required comparison to be made, and hence it eliminates one of the most serious difficulties of the station engineer who is endeavouring to maintain a uniformly high standard of operating efficiency. This is perhaps its most immediate practical benefit, but it also enables the constant losses, both in the engine-room and the boiler-room to be determined with close accuracy. It shows what would be the extra cost in fuel of carrying any additional load of which the plant is capable, and therefore enables the manager to know the minimum price at which he could supply such extra power without actual financial loss, or the maximum price he could afford to pay for the purchase of power which could be produced by his existing plant and staff. The method further enables the effect of any increase or decrease of load upon the coal consumption to be forecasted with great accuracy. It also shows the limits of efficiency to which the boiler-room, the engine-room, and the whole plant are respectively tending, and, in short, it gives the engineer a grasp of the operation of his plant as a whole, and a continuous check upon its operating efficiency, such as are afforded by no other means. It may be added, too, that the method can be used to form the basis of a simple and satisfactory scheme for the payment of bonuses in accordance with efficiency.

Data Required. The data which are required, in order that the information mentioned above may be obtained by the author's method of analysis, are very simple. They are as follows ; firstly, the weight of coal consumed on each shift ; secondly, the weight of water evaporated on each shift, and thirdly the electrical output in kw.h. on each shift. It is better that the net electrical output, after the power used in the station itself has been deducted should be taken, rather than the gross power as measured at the generator terminals, but some engineers adopt the latter quantity on the grounds of simplicity.

Plotting the Observations. To inaugurate the system, three sheets of squared paper are required, the size most generally convenient being quarto with half-inch squares subdivided into tenths. One of these sheets, which will be called the "Coal Chart" is marked off along its lower edge to a scale of "kilo-watt-hours per shift," while the left-hand vertical edge is similarly marked off to a scale of "Pounds of coal per shift." Reference to Fig. 73 will make this clear. The second chart,

known as the "Steam Chart" is prepared in a similar way, except that the left-hand edge is marked off to a scale of "Pounds of water per shift," the lower edge being marked off to a scale of kw.h. per shift as before. This chart is shown in Fig. 74. The third chart, shown in Fig. 75, is known as the

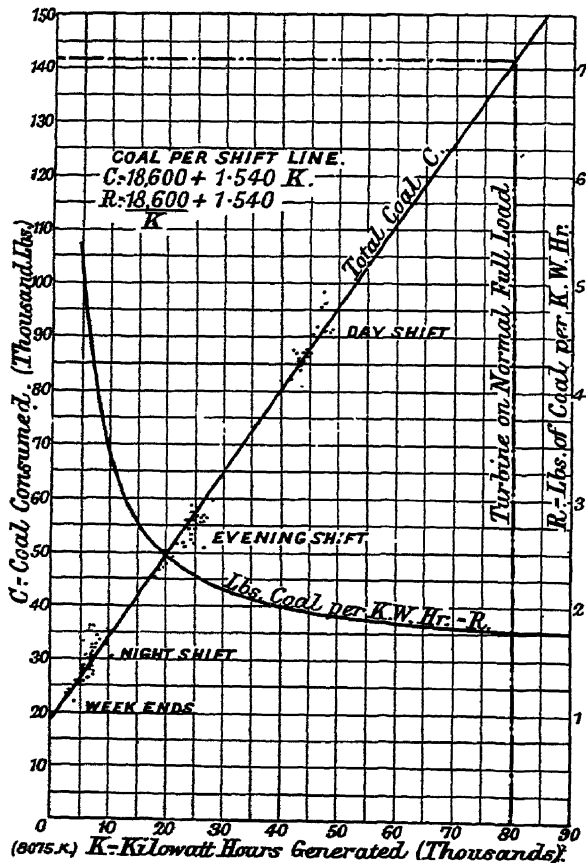


FIG. 73

"Evaporation Chart." It is not absolutely necessary, as all the information it contains can be deduced from the other two, but as it illustrates certain facts in a graphic manner, and especially as it serves as a check upon the accuracy of the other charts it should always be prepared. The vertical side of the Evaporation Chart is divided, as the diagram shows, into a scale of "Pounds of coal per shift" and the base into a scale of "Pounds of water per shift."

Having prepared these charts, the next step is to record upon them the operating results over a certain period of time, a month being often adopted. As the returns come in at the end of every shift, a dot is made upon the coal chart corresponding both to the coal consumed and the electrical output

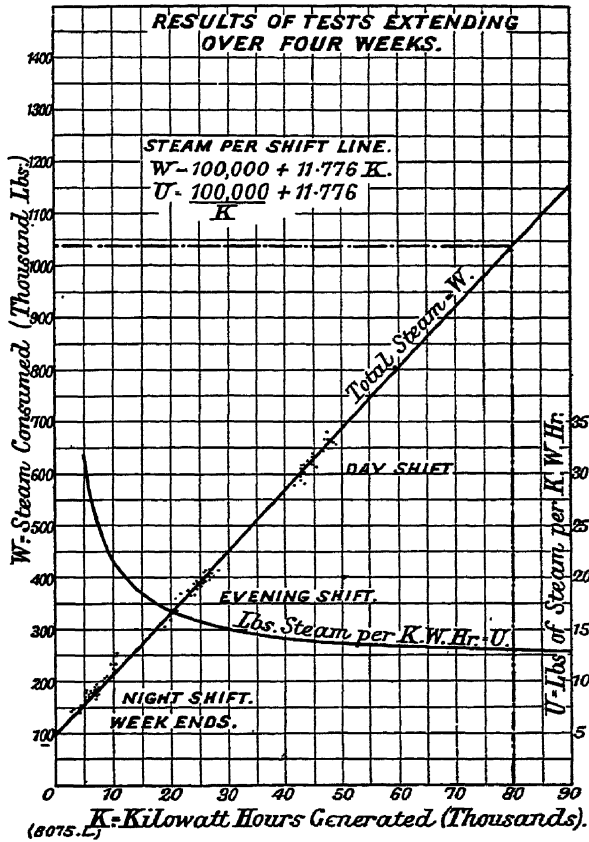


FIG. 74

during that shift. Similarly on the steam chart, a dot records the pounds of steam used and the electrical output, while on the evaporation chart the dot marks the coal burnt and the water evaporated. At the end of four weeks each chart will contain eighty-four dots, and it will be seen that these lie in a sloping direction across the charts, as in Figs. 73 to 75. Taking the three charts in turn, the line which lies most evenly among the dots must now be drawn in. The best position for this

line is most easily found by drawing a straight line upon a strip of tracing paper and then moving the strip about over the chart until the best position of the line has been decided on.

The Parsons Line. The three lines, which are known as the "Parsons lines" form the basis of the analysis of the operating

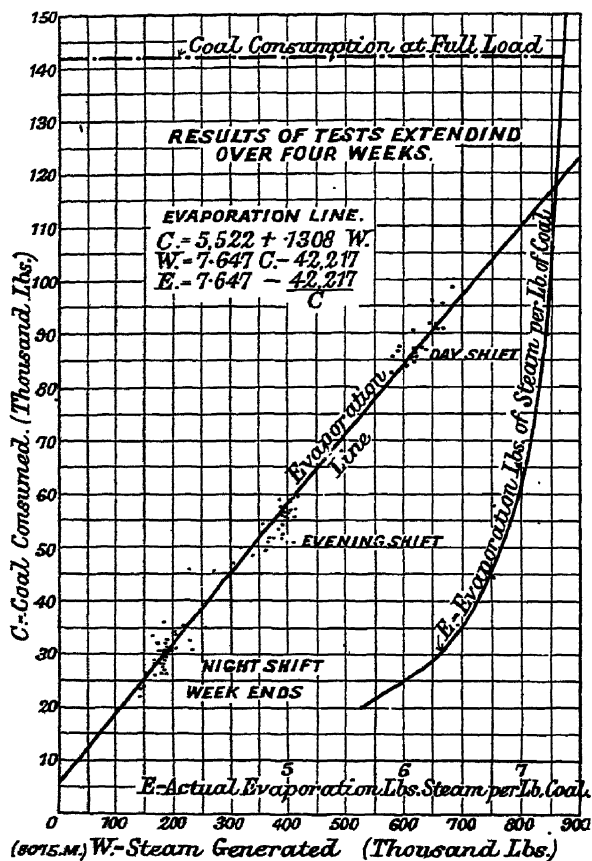


FIG. 75

results, but once they have been established for any station they form an obvious criterion of operating efficiency and may be used as such by engineers who do not care to examine their significance further. Each line clearly represents the average performance of the station in respect of coal consumption per kw.h., water consumption per kw.h., or evaporation per lb. of coal. Hence, whenever the dot recording a shift's performance is found to lie above the Parsons line, the efficiency on that

shift is so much below the average and vice versa. It will be noted that the difficulty of comparing efficiency at different outputs has been entirely overcome by this simple means. Even this elementary use of the lines has been found in practice to have been enormously useful in improving operating results, so much so indeed, that new lines have had to be determined for the stations concerned as the old ones no longer represented a fair standard of performance.

What the Lines Show. Each of the Parsons lines can, of course be represented by a simple linear equation, which may be deduced from the corresponding chart by the method given in any text-book of co-ordinate geometry. The diagrams which are given in Figs. 73, 74, and 75 represent the actual operating results of Blackburn Power Station and are reproduced by the courtesy of *Engineering*.

Coal per kw.h. The equation to the coal-line in Fig. 73 is as follows—

$$C = 18,600 + 1.540 K \quad . \quad . \quad . \quad (1)$$

In which C represents the number of lbs. of coal burnt per shift, and K the output in kilowatt-hours during the same period.

Steam per kw.h. The equation to the steam-line in Fig. 74 is—

$$W = 100,000 + 11.776 K \quad . \quad . \quad . \quad (2)$$

in which W represents the quantity of water evaporated per shift and K is the same as before.

Evaporation per lb. of Coal. From these two equations a third may be deduced, which may be written in either of the following forms, these being identical—

$$C = 5,522 + 0.1308 W \quad . \quad . \quad . \quad (3)$$

$$\text{or } W = 7.647 C - 42,217 \quad . \quad . \quad . \quad (4)$$

Equation No. (3), connecting the coal and steam consumptions together, must obviously represent the evaporation line in Fig. 75. If it does not do so, the best position for one or more of the lines has not been found, and they must be adjusted until the equations to all the three are consistent with one another. Hence it is advisable not to draw the lines on the charts in ink, until their final positions are decided on.

Analysis of Records. The positions of the lines, and the corresponding equations having been determined, we can now proceed to discuss the information they give, and we will deal

in order with the various points mentioned at the beginning of this article. In the first place, equation (1) enables us to calculate what may be called the standard coal consumption for any output, so that we have a figure with which to compare the actual coal consumption on any shift. Similarly from equation (2) we can calculate the standard steam consumption for any output, and check the performance in this respect. Equation (4) enables us to calculate the standard evaporation, for any particular weight of coal burnt, and thus to check the operating efficiency of the boiler-house on any shift.

From equation (1) we see that the total quantity of coal burnt on any shift may be regarded as made up of two portions, firstly a constant amount of 18,600 lbs., which is the same whatever the output, and secondly an additional amount of 1.54 lbs. for every kilowatt-hour turned out. Obviously, if there was no electrical output, 18,600 lbs. of coal would still be consumed per shift, and this amount therefore is the quantity required to make up the "no-load" losses of the station. These losses include radiation, condensation, and chimney losses, as well as the auxiliary power and steam required to maintain the station in a condition to take load without notice, that is with one generator running idly. Similarly from equation (3) we see that if no water were to be evaporated on a shift, 5,522 lbs. of coal would still be necessary to maintain the boilers in a condition to supply steam on demand. This quantity of 5,522 lbs. of coal is that required to counterbalance the constant radiation and other losses in the boiler-room and to maintain steam pressure. Hence the difference between the total no-load loss of 18,600 lbs. of coal per shift, and the boiler-room loss of 5,522 lbs., namely 13,078 lbs. per shift, represents the coal burnt to make good the no-load losses in the engine-room.

It is clear from equation (1) that any additional load which may be carried by the station will involve the consumption only of 1.54 lbs. of coal for every extra kilowatt-hour turned out. If this load can be carried without increasing capital or labour charges or involving any extra expense other than that for fuel, it can be sold per unit at the cost of 1.54 lbs. of coal without money being lost by the transaction. Conversely it would not pay the power station to give more than this price for current purchased, unless some saving in labour or otherwise could be made by buying current.

Limit of Efficiency. Referring again to equation (1) it

will be noted that as the output of the station increases, the second term in the equation becomes larger and larger in comparison with the first, and with a very large output indeed the constant quantity of 18,600 lbs of coal per shift would be negligible. Hence the station is tending ultimately to an efficiency which is represented by the consumption of 1.54 lbs. of coal per kw.h. This, of course, would only be reached with an unlimited output, and provided that the operating conditions remained the same. The figure is thus a hypothetical one, and may be termed the "coal consumption rating" of the station. From equation (2) we see, in a similar way, that the steam consumption is tending towards a corresponding limit of 11.776 lbs. per kw.h., which would be reached when the load was so great that the no-load losses were negligible. This is the "steam consumption rating" of the machinery. A third limiting condition is made evident by equation (4) which shows that the evaporation becomes more and more nearly 7.647 lbs. of water per lb. of coal as the load on the boilers increases.

Bonus System for Power Stations. The final claim which was made for the author's system was that it formed a convenient basis for a simple and satisfactory bonus scheme. Space does not permit an exhaustive discussion of this aspect of the subject, but the underlying principle is as follows. At the end of every week, the electrical output of each shift of men would be totalled and the standard coal consumption corresponding thereto would be calculated from equation (1). If the actual coal consumption was lower than the standard, the men's wages would be increased by the same percentage as the standard was beaten by. Alternatively the boiler-house staff might have their bonuses computed from the evaporation equation (4), since they have no control over the utilization of the steam they make.

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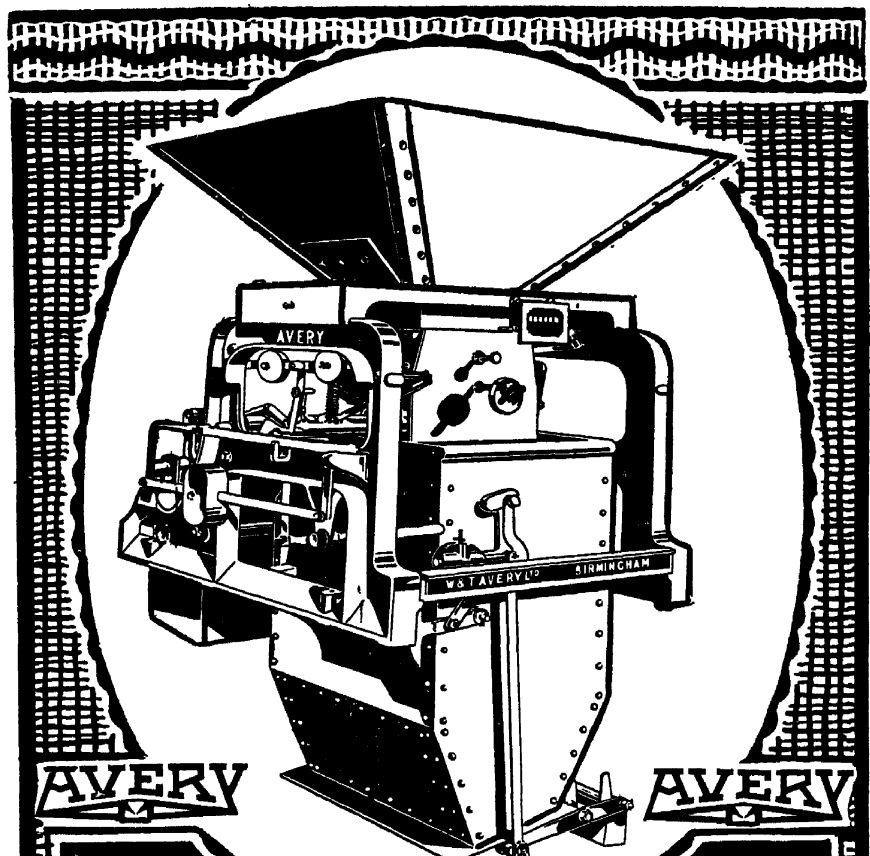
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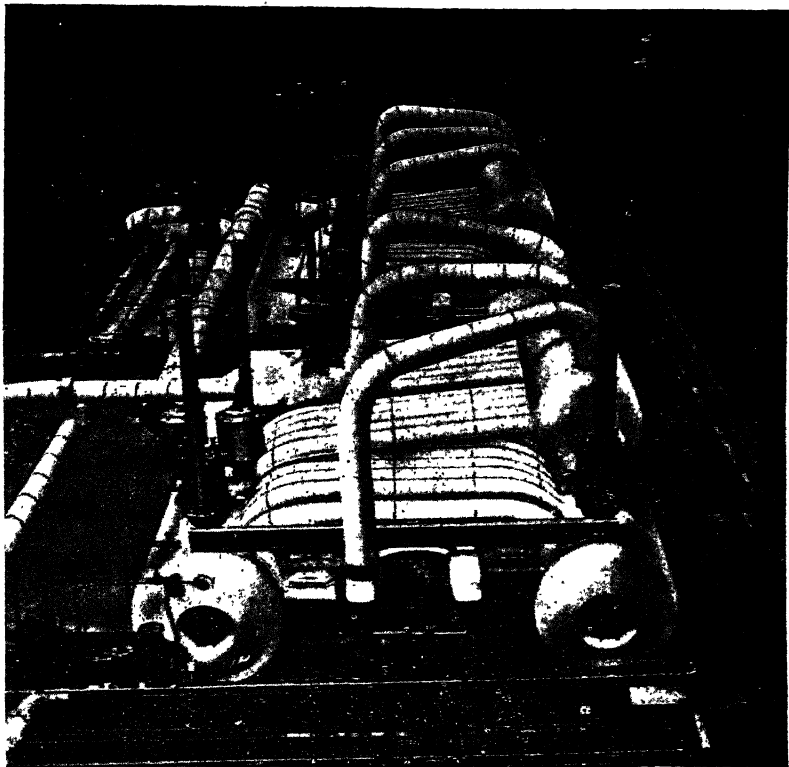
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